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PREFERRED ORIENTATION OF CALCITE IN YULE MARBLE

FRANCIS J. TURNER

ABSTRACT. A detailed account of the fabric of Yule marble is given for later comparison with the fabric of the same rock artificially deformed. Preferred orientation of the following crystal directions is described: optic axis; visible {01$\bar{1}$2} lamellae; edges of intersecting {01$\bar{1}$2} lamellae; edges between {01$\bar{1}$2} and {10$\bar{1}$1}; edges between {01$\bar{1}$2} and {0001}; optic axis within definite twin lamellae. The nature and possible origin of space-lattice orientation of the calcite grains is discussed. It is shown that many lamellae of the form {01$\bar{1}$2} are probably due to translation rather than to twin gliding. Many lamellae are believed to have formed as a result of late relatively mild deformation subsequent to that responsible for the observed space-lattice orientation expressed by optic axes diagrams.

INTRODUCTION

IN a series of compression tests carried out at high confining pressures, Griggs (1936; 1940) succeeded in shortening marble and limestone columns by as much as 30-50%. He also recorded briefly some of the changes observed in the microscopic fabric of one of the test materials, viz. a pure marble from a quarry at Yule Creek, Colorado, owned by the Vermont Marble Company (see also Knopf, 1943). The committee on experimental deformation of rocks, set up under chairmanship of Mrs. E. B. Knopf by the National Research Council, has urged that this program of research be continued (Knopf, 1946); and as a preliminary step Knopf (1949) has recorded the results of a petrofabric analysis of Yule marble. Since this latter work raised or left unanswered several questions as to the state of preferred orientation of calcite in the marble, and the crystallographic identity of deformation lamellae in individual grains, Mrs. Knopf suggested to the present writer that he investigate the fabric of the same rock independently and in as full detail as possible.

The original block of marble which furnished the test cylinders for the experiments of Griggs, 1936-1940, was a geographically oriented block collected by E. B. Knopf from the

Yule quarry. The sections for the present study were cut from a second block of Yule marble, originally unoriented, which was kindly provided by Mr. Harold Ladd Smith of the Vermont Marble Company. Preliminary petrofabric analysis of this second block by Dr. H. Mikami at Yale University showed that its fabric conforms so closely with that of Griggs' original block as to allow its geographic orientation to be reliably established. Three mutually perpendicular sections were cut from the second block for the present investigation. They are approximately parallel to the three sections used by Knopf (1948) in her fabric study of the material used in Griggs' experiments, and have been labelled correspondingly.

All grains measured in the present study have been identified and recorded on three large photomicrographs showing the major portions of the three sections enlarged to 27 diameters. These photographs were made by Dr. H. Mikami, research geologist for the E. J. Lavino Company of Pennsylvania.

The writer's thanks are gratefully acknowledged to Mrs. E. B. Knopf for suggesting the problem and supplying the material, for frequent advice and consultation as the work progressed and for permitting access to unpublished results of her own work on Yule Marble. His thanks are also due to Dr. H. Mikami, Mr. Harold Ladd Smith and the Vermont Marble Company for assistance acknowledged above, and to the E. J. Lavino Company by whose courtesy facilities were granted to Dr. Mikami for preparing the photomicrographs.

For reference purposes the following details of the research material (given by Mrs. Knopf) are recorded.

Locality:	Quarry on west side of Yule Creek, 3 miles south of Marble, Gunnison County, Colorado.
Field data:	(a) Joints: (1) Main set strikes N65°E and dips 80°N.W. (2) Discontinuous joints in zones *en echelon* strike N55°W and dips 70°S.W. (b) Foliation strikes N5°E and dips approximately vertically.
Physical properties:	Pure calcite marble, free from dolomite; G = 2.7; porosity low, 0.15%; permeability fairly high (water penetrates 1.5 inches in 70 minutes).

The previous work of Knopf (1948) has demonstrated that the fabric of Yule marble is substantially homogeneous, and has given a clear picture of the state of preferred orientation of the optic axis and of all visible lamellae (whether due to twinning, translation or cleavage) in the component grains of calcite. The purposes of the present paper are:

1. to check the data recorded by Knopf;
2. to identify the crystallographic orientation of visible lamellae in calcite grains;
3. to record in as full detail as possible the state of preferred orientation of calcite in Yule marble, for subsequent comparison with fabrics of artificially deformed specimens of the same rock;
4. to record such additional data as might throw light on the mode and time of origin of visible lamellae in calcite of Yule marble.

The first part of the paper is descriptive, and includes an outline of the methods used, followed by a record of measured fabric data. Then follows a section in which the writer's tentative interpretation of the data is put forward.

LABORATORY PROCEDURE

Record of Measurements. As seen by microscopic comparison of the three sections, the single plane of foliation is defined by dimensional subparallel alinement of interlocking irregularly discoidal grains of calcite whose smallest dimensions average between one half and one third the greatest dimension. The three mutually perpendicular oriented sections were cut approximately parallel (Q) and perpendicular (P and R) to the foliation, as shown diagrammatically in Figure 1. The P section is vertical, and the R section horizontal. The tendency for calcite grains to be somewhat elongated in the plane of foliation is seen more distinctly in the R section than in P, while section Q shows a slight tendency for grains to be elongated in the horizontal (NS) direction. This confirms the previous record of a faintly developed subhorizontal (NS) lineation in the plane of foliation. The axes of the calcite fabric are thus provisionally identified as follows: *a* is vertical; *b* is NS; *c* is EW (cf. fig. 1).

On each section measurements were made on all grains, regardless of shape or size, lying on a number of separate

approximately linear traverses. Each grain was numbered and identified on the corresponding photomicrograph, and a full record of optical and crystallographic measurements for each numbered grain has been kept. Elemental orientation diagrams each showing the orientation of a given optical or crystallographic direction for between ten and thirty numbered grains have also been retained.

Details of traverses and of grains measured in each section are as follows:

Section P: 100 grains within an area 13mm. x 9mm.: two vertical traverses (parallel to trace of foliation), 6mm. and 8mm. long; one EW traverse (transverse to foliation) 4mm. long; one traverse including all grains within an area 4 mm. x 1 mm.

Section Q: 90 grains within an area 10mm. x 5 mm: two vertical traverses 7mm. and 10mm. long; one traverse including all grains within an area 2mm. x 2mm.

Section R: 150 grains within an area 13mm. x 10mm.: two EW traverses (transverse to trace of foliation), 12mm. and 7mm. long; one traverse including all grains in an area 5mm. x 3mm.

Since the fabric has already been shown to be homogeneous, it was thought advisable to concentrate on detailed investigation of relatively few (340) grains. In each crystal the position of the optic axis was measured and checked; all visible deformation lamellae and the more obvious cleavage directions were measured and crystallographically identified; additional but not obvious lamellae were searched for wherever within the accessible field of view; individual peculiarities such as relative grain size, bending of certain sets of lamellae, development of obvious twinning in other sets, relation of lamellae in adjoining grains and relation of lamellae to grain outlines were recorded wherever observed. Yet other crystallographic directions were determined graphically from the positions of the optic axis and the poles of lamellae or cleavages as plotted on a Schmidt projection net.

Finally elemental and collective orientation diagrams were prepared for each of the following directions, as determined in each of the three oriented sections.

1. Optic axis = vertical crystal axis.
2. Poles of visible lamellae of the form $\{01\bar{1}2\} = e$.
3. Edges $[e : c]$, i.e. edges between visible lamellae $\{01\bar{1}2\}$ and the basal pinacoid $\{0001\}$.
4. Edges $[r : r'] = [r : e]$ i.e. edges between visible lamellae $\{01\bar{1}2\}$ and either of the adjoining unit rhombohedron faces $(10\bar{1}1) = r$ or $(\bar{1}101) = r'$.
5. Edges $[e : e']$, i.e. edges between visible faces of the form $\{01\bar{1}2\}$
6. Edges $\underline{\perp [e : e']}$, i.e. the line drawn in the basal pinacoid (0001) perpendicular to the edge between visible faces of the form $\{01\bar{1}2\}$.
7. The optic axis within each observed $\{01\bar{1}2\}$ lamella, assuming that the latter is due to twinning.

Additional diagrams were also prepared for optic axis, pole of $\{01\bar{1}2\}$ lamella, new position of optic axis, and glide-line $[r : r'] = [e : r]$ in those grains in which twinning on $\{01\bar{1}2\}$ could be demonstrated beyond doubt.

Orientation diagrams depicting data for any one type of crystallographic direction (e.g. normals to lamellae) were prepared separately for each of the three sections examined. For detailed comparison, and for preparing collective diagrams based on measurements in more than one section, it was found more satisfactory to rotate the plotted points individually through 90°, than to rotate contoured diagrams. This procedure has therefore been followed throughout, wherever rotation seemed desirable.

Measurement of the c *crystal axis* [*0001*]. Several difficulties attend location of the *c* crystal axis of a calcite grain with a universal stage. The extreme birefringence of calcite makes it difficult to differentiate quickly between fast and slow directions in a given grain unless the section is thin. Moreover, for some orientations, especially where the *c* axis is inclined at a small angle to the plane of sections, the grain may remain in extinction through as much as 10° of tilt. An

added difficulty in the case of Yule marble arises from the distinctly biaxial condition of many grains ($2V = 0° — 15°$). The procedure outlined below was found generally satisfactory in minimizing errors arising from these causes. Repeated checking of angles between the poles of measured lamellae (or cleavage cracks) and the *c* axis, show that the position of the latter can always be located within two or three degrees, i.e. sufficiently accurately for requirements of fabric analysis.

(1) The section is mounted between glass hemispheres having refractive index 1.557, using colorless mineral oil ("albolene") as mounting oil. All measurements of optic axes are made with the optic axis in the E.W. vertical plane, so that light (vibrating N.S.) is transmitted entirely as the ordinary ray ($\gamma = 1.659$). The stage may be tilted up to 60° without total reflection; but all tilts must be corrected for difference in refractive index of hemispheres and calcite. Thus a reading of 40° is reduced to 37°; 25° is reduced to 23°, and so on.

(2) With both axes of tilt at the zero position, the calcite grain is first rotated on the innermost stage axis to extinction, with the fast direction (trace of the optic axis) E.W. [In identifying the fast direction with the aid of a quartz wedge, the position of compensation may usually be recognized clearly if the iris diaphragm in the objective is first stopped down. The test is not decisive if the section is thick and is cut nearly parallel to the optic axis. In this case, however, the apparent relief of the section is obviously higher when the slow direction is N.S. than when it lies E.W.]

(3) The stage is now tilted through about 30° on E.W. and the section once more becomes illuminated (unless the optic axis already coincides with the E.W. stage axis). Tilting on N.S. to extinction now brings the optic axis either parallel to E.W. or vertical. The latter case is readily distinguished by the manner in which the order of interference color falls through first order greys to the extinction position. If necessary, it may be confirmed by tilting back on E.W. to the zero position, unclamping the stage, and rotating on the main vertical axis (microscope axis). The grain, of course, remains dark only if the optic axis is vertical.

(4) A useful check may be obtained by measuring three or more directions of ordinary ray vibrations. The stage is

set with E.W. at zero and is tilted about N.S. to 20° from the left. The section is now rotated on the innermost vertical axis until it reaches extinction with the slow direction (ordinary ray) E.W. This procedure is repeated independently with N.S. first at zero, and then tilted 20° from the right.

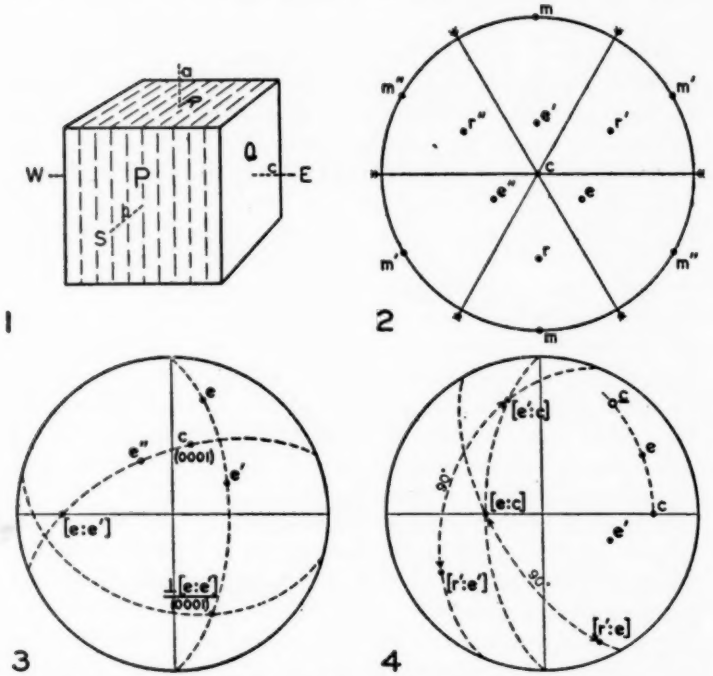

Figure 1. Section block of Yule marble showing orientation of the three sections P, Q, and R with respect to geographic coordinates and fabric axes *a*, *b*, *c*.

Figure 2. Equal-area projection showing relative positions of poles of faces of the forms $\{10\bar{1}0\} = m$, $\{10\bar{1}1\} = r$, $\{01\bar{1}2\} = e$, and $\{0001\} = c$, in calcite.

Figure 3. Equal-area projection showing relative positions of poles of faces of forms $\{01\bar{1}2\} = e$, and $\{0001\} = c$; the edge $[e : e']$ between two faces of the form $\{01\bar{1}2\}$; and the normal to this edge lying in the face (0001), i.e. $\frac{\perp [e : e']}{(0001)}$ Drawn for calcite.

Figure 4. Equal area projection showing edges $[e : c]$ and $[e' : c]$ between (0001) and faces of form $\{01\bar{1}2\}$; edges $[r' : e]$ and $[r' : e']$ between faces of the forms $\{01\bar{1}2\}$ and $\{10\bar{1}1\}$; optic axis $\underline{c}$ of lamella twinned on e. Drawn for calcite.

The three corresponding points plotted on the projection net should lie on a great circle whose pole is the point of emergence of the *c* axis. The writer has found this procedure somewhat the more satisfactory of the two in cases where the optic axis is inclined at a low angle to the plane of the section, or where the grain is either biaxial or strained (as indicated by undulose extinction.)

Measurement of lamellae and cleavage. A lamella or cleavage plane is observed in the normal manner by bringing its trace parallel to either cross-hair and tilting to the vertical position about the corresponding axis of the stage. The other titling axis is kept at the zero position. Lamellae of the form $\{01\bar{1}2\}$ are more readily observed between crossed nicols, but cleavages $\{10\bar{1}1\}$ are more sharply defined when seen in ordinary light. Partial stopping down of the iris diaphragm in the objective may sharpen definition.

Wherever an individual lamella shows alternate illumination and extinction on rotation of the whole stage, and the lamella and the main portion of the grain give symmetrical extinction angles, the lamella is recorded as clearly due to twinning. In Yule marble the majority of lamellae of the form $\{01\bar{1}2\}$ are not obviously twinned. When tilted into the vertical plane they appear as hair-sharp lines, rather than as lamellae. But they may usually be distinguished from cleavages $\{10\bar{1}1\}$ by their greater individual continuity and by a tendency to remain clearly visible even when tilted at angles of as much as 30° from the vertical plane.

Each set of cleavages or lamellae is identified with certainty as belonging to either $\{10\bar{1}1\}$ or $\{01\bar{1}2\}$ by plotting its pole and measuring the angle between the pole and the *c* axis. The following interfacial angles (measured between poles of faces) are of use in this connection (cf. fig. 2).

$$c \wedge r,\ (0001) \wedge (10\bar{1}1) = 44\tfrac{1}{2}^\circ$$
$$c \wedge e,\ (0001) \wedge (01\bar{1}2) = 26\tfrac{1}{4}^\circ$$
$$e \wedge e',\ (01\bar{1}2) \wedge (1\bar{1}02) = 45^\circ$$
$$r \wedge r',\ (10\bar{1}1) \wedge (\bar{1}101) = 75^\circ$$
$$e \wedge r,\ (01\bar{1}2) \wedge (10\bar{1}1) = 38^\circ$$

Note that the interfacial angles between a face $(01\bar{1}2)$ and the adjacent faces, $(10\bar{1}1)$ and $(\bar{1}101)$ are 38°; but the third unit rhombohedron face $(0\bar{1}11)$ is co-zonal with $(01\bar{1}2)$ and the intervening face (0001); so that the angle $(01\bar{1}2) \wedge (0\bar{1}11)$ is $70\tfrac{3}{4}^\circ$.

When one or two faces of the form $\{01\bar{1}2\}$ have been measured and plotted, the positions of the remaining faces or face of the same form may be located on the projection. The innermost rotation axis and one tilting axis of the stage are now set at appropriate angles and the section is searched, to make sure that lamellae parallel to the unrecorded face or faces have not been overlooked.

Location of edges $[e:e']$ *and* $\frac{\perp[e:e']}{(0001)}$. Where two sets of lamellae e and e' belonging to the form $\{01\bar{1}2\}$ have been measured in one grain, their line of intersection is located graphically on the projection net. Its projection ($[e:e']$ in fig. 3) is the pole of the great circle which includes the poles of both lamellae e and e'. The direction within (0001) which is normal to the intersection $[e:e']$, here designated $\frac{\perp[e:e']}{(0001)}$, is the pole of the great circle which includes $[e:e']$ and the pole of (0001). It is also parallel to one of the three horizontal crystal axes, i.e. to the edge between the basal pinacoid and the third rhombohedron e'' of the form $\{01\bar{1}2\}$. These relations are shown in figure 3.

Location of edges $[e:c]$ *and* $[e:r]$. For each measured set of faces of the form $\{01\bar{1}2\}$, the edge of intersection with the basal pinacoid (0001) is located graphically as the pole of the great circle on which the c axis and the pole of the lamella both lie (fig. 4). The glide direction for normal lamellar twinning, namely $[r:r'] = [e:r]$, is normal to the edge $[e:c]$ and lies within the plane e. It may be located by measuring off an angular distance of 90° from the point $[e:c]$ along the great circle representing the e lamella. Where more than one set of lamellae $\{01\bar{1}2\}$ is developed in one grain, the observed angles between corresponding edges $[e:c]$ and $[e':c]$, or $[e:r]$ and $[e':r]$ afford a useful test as to accuracy with which lamellae and optic axis were located in the first instance. The true values are:

$$[e:c] \wedge [e':c] = 60°$$
$$[e:r] \wedge [e':r] = 78°$$

Location of c *crystal axis in twin lamellae.* In Yule marble twin lamellae are seldom wide enough to allow the position of the optic axis within a lamellae to be located directly. Since, however, the crystallographic directions of a lamella and those

of the main crystal in which it occurs are related as by reflection across the twin plane $\{01\bar{1}2\}$, the optic axis in the lamella may be located graphically. Rotate the projection until the pole of the lamella and the projection of the *c* axis of the main crystal lie on a great circle. Then the optic axis within the twin lamella emerges at a point $26\frac{1}{4}^\circ$ from the lamella pole on the same great circle (fig. 4).

RESULTS OF PETROFABRIC ANALYSIS OF YULE MARBLE

Preferred orientation of c *axis* [*0001*]. The orientation of all vertical crystal axes measured (340) is shown in a collective diagram, figure 5. Corresponding elemental diagrams showing the same data plotted separately for each of the three sections are reproduced for comparison (figs. 6, 7, 8). The most significant feature of these diagrams is a constant but somewhat dispersed maximum coinciding with the pole of the foliation. Submaxima are on the whole unimportant, and there seems to be no indication of a girdle pattern in the fabric. A count of the plotted axes shows that 52% lies at angles ranging from 55° to 90° to the plane of foliation. Within this sector the axes are fairly evenly distributed except for a slightly denser concentration at approximately 90° to the foliation. Separate plots of axes of smallest and largest grains respectively show no significant differences.

There is general agreement between these diagrams and those previously published by E. B. Knopf (Griggs, 1940, p. 1006, fig. 1). The latter show the main axes maximum divided into submaxima which are asymmetrically situated with respect to the pole of the foliation; moreover there is a weak broken girdle in Knopf's diagrams. Neither of these features is reproduced in the writer's diagrams.

Preferred orientation of lamellae $\{01\bar{1}2\}$. Since lamellae or cleavages inclined at angles of less than about 35° to the plane of the section are either invisible or cannot be located accurately, there is a central blank area or blind spot in any orientation diagram constructed for poles of lamellae observed in only one section. In Yule marble a fairly complete picture of the state of preferred orientation of lamellae $\{01\bar{1}2\}$ may be obtained from any section (e.g. P and R) cut normal to the foliation. In these, the *c* crystal axis in most grains lies close to the plane of the section, so that all three sets of

lamellae of the form $\{01\bar{1}2\}$ fall within the field of visibility. Of the grains measured in sections P and R, 73% have their *c* axes inclined at angles of less than 30° to the plane of the section, and so satisfy this condition completely. Only 12% have their optic axes so steeply inclined (at 50°-90°) to the section, that at least one set of $\{01\bar{1}2\}$ lamellae must lie outside the field of accurate measurement. But even in these, lamellae may be located indirectly, provided they become visible at high angles of tilt. The trace of such a lamella is brought parallel to the N.S. crosshair by rotating the section

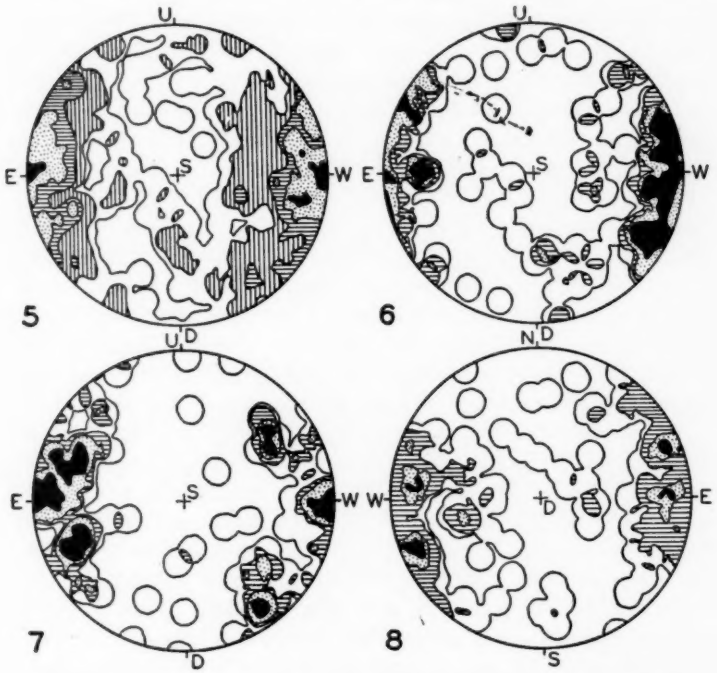

Figure 5. [0001] = *c* axis for 340 grains measure in sections P (100), Q (90) and R (150), and plotted on P. Contours at 4%, 3%, 2%, 1%, 0.3%, per 1% area.

Figure 6. [0001] for 100 grains in section P. Contours at 4%, 3%, 2%, 1%.

Figure 7. [0001] for 90 grains in section Q, rotated into plane of section P. Contours at 4%, 3%, 2%, 1%.

Figure 8. [0001] for 150 grains in section R. Contours at 6%, 4%, 2%, 0.7%.

on the innermost axis and tilting on the N.S. axis to a high angle, with the E.W. axis set in the zero position. The pole of the lamella may now be plotted in the appropriate position $26\frac{1}{4}^\circ$ distant from the *c* axis of the same grain.

Figure 9 is a collective diagram based on all measured lamellae (a total of 571) in the three oriented sections. Of these, 188 were measured in section P; 136 poles measured in Q and 247 in R were rotated into the plane P. The collective diagram should give an adequate picture of preferred orientation of $\{01\bar{1}2\}$ lamellae developed in this specimen of Yule marble. Its main feature, viz, a broad sector of concentration around the pole of the foliation, is reproduced in the corresponding elemental diagrams (figs. 10-13), if allowance is made for the blind spot surrounding the pole of the foliation in figure 11. A faint but distinct girdle pattern may be discerned particularly in figures 9, 12 and 13. The girdle axes (X, fig. 9) is unrelated to any of the recorded elements of the megascopic fabric. Subdivision of the sector of concentration into two main maxima (Y and Z, fig. 9) is shown independently in figures 10 and 13 and may, therefore, be significant. The lamellae diagrams of Knopf (1949) likewise show a maximum divided about the pole of the foliation. This author did not distinguish, however, between $\{01\bar{1}2\}$ lamellae and $\{10\bar{1}1\}$ cleavages. So that her lamellae diagrams are not strictly comparable with those accompanying this paper.

Of the 250 grains measured in sections P and R, 5% lack visible $\{01\bar{1}2\}$ lamellae; 30% show one set, 50% two sets, and only 15% three sets of lamellae. We have already noted that over 70% of the grains in these two sections are so oriented that all three sets of lamellae, if developed, would be accessible for measurement. It would thus appear that development of visible lamellae has been strongly selective. Consequently, figures 9 to 13 do not express completely the state of preferred orientation of the calcite *space-lattice* in Yule marble. Their pattern is determined partly by the existing preferred orientation of the lattice, but partly, too, by the selective mode of development of the measured lamellae. That this selective influence is not a random one is suggested by the distinct though weak girdle pattern and accompanying concentration of lamella poles in the upper sectors of figures 9 to 13. No such features are apparent in the corresponding axes diagrams such as figure 5.

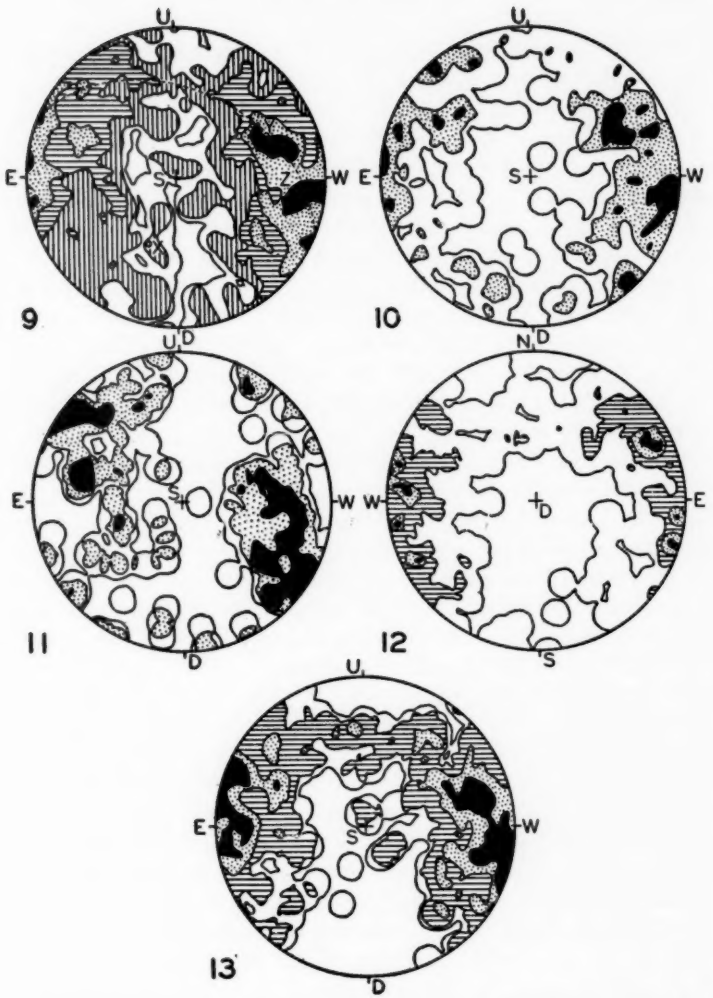

Figure 9. Poles of {01$\bar{1}$2} = *e*: 571 lamellae measured in sections P (188), Q (136) and R (247), and plotted on P. Contours at 3%, 2%, 1%, 0.5%, 0.2%, per 1% area.

Figure. 10. Poles of {01$\bar{1}$2}, 188 lamellae in section P. Contours at 3%, 1.6%, 0.5%.

Figure 11. Poles of {01$\bar{1}$2}, 136 lamellae in section Q, rotated into plane of section P. Contours at 3%, 1.5%, 0.7%.

Figure 12. Poles of {01$\bar{1}$2}, 247 lamellae in R. Contours at 5%, 4%, 2%, 0.4%.

Figure 13. Poles of {01$\bar{1}$2}, 247 lamellae in R, rotated into plane of section P. Contours at 3%, 2%, 1%, 0.4%.

Preferred orientation of edges [$e : e$]. Any preferred orientation of the calcite lattice, in addition to the general E.-W. alinement of optic axes already noted, should be reflected in orientation diagrams for edges between $\{01\bar{1}2\}$ lamellae and basal pinacoid; for these also coincide with one or other of the three horizontal crystal axes in any given grain. The orientation of such edges for all visible lamellae in the P and R sections is shown in figures 14 and 15 respectively. The corresponding diagram for section Q is in all respects similar and has been omitted. The broad ill-defined vertical N.-S. girdle and accompanying E.-W. minimum may be correlated with the general E.-W. alinement of optic axes depicted in figure 5. But the edges are not uniformly distributed within the N.-S. girdle. In all three diagrams, more edges dip south than dip north, so that there is a greater concentration of poles in the S.-D. than in the N.-D. sector of the girdle. This condition may be correlated with the same selective development of deformation lamellae as is indicated by the lamellae diagrams.

To evaluate the possible influence of space-lattice orientation of the calcite grains upon the pattern of figure 14 and 15, the poles of all three $\{01\bar{1}2\}$ faces were located (by direct measurement or by graphic construction) in 97 out of the 100 measured grains of section P*. The state of preferred orientation of the corresponding edges, $\{0001\}:\{01\bar{1}2\}$, is shown in figure 16, in which the poles are more uniformly distributed through the N.-S. girdle than is the case in figures 14 and 15. This is strong evidence against preferred orientation of horizontal crystal axes in the calcite fabric; but it is still conceivable that a weak orientation of horizontal axes exists but is obscured by the imperfect state of alinement of vertical axes shown by the spreading maximum of figure 5. This latter possibility has been tested by plotting all three edges $\{0001\}:\{01\bar{1}2\}$ for all grains (10 in each section) whose optic axes lie within 12° of the ideal horizontal E.-W. direction which corresponds to the maximum in figure 5. As shown in figure 17, these edges are almost uniformly distributed in the N.-S. vertical plane. In two sections (P and Q) some degree of orientation may be detected; but the maximum concentrations for one section coincide with minima for the other, while in the third section (R) the distribution is random.

* In the three remaining grains, neither $\{10\bar{1}1\}$ cleavages nor $\{01\bar{1}2\}$ lamellae were visible.

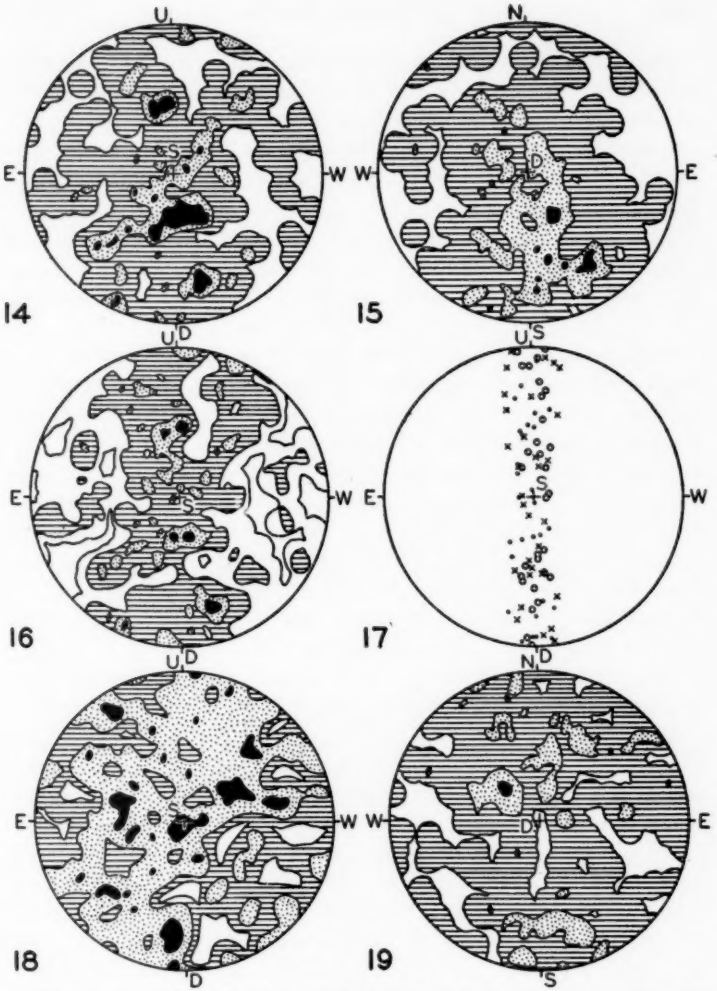

Figure 14. Edges $[e:c]$, in 188 lamellae in P. Contours at 3%, 2% 0.5%, per 1% area.

Figure 15. Edges $[e:c]$, in 247 lamellae in R. Contours at 4%, 2%, 0.4%.

Figure 16. All three edges $[e:c]$ in 97 grains (out of a total 100) in P. Total number of edges = 291. Contours at 3%, 2%, 1%, 0.4%.

Figure 17. All three edges $[e:c]$ for 30 grains whose optic axes fall within 12° of the E.-W. horizontal direction. Dots represent poles measured in section P; open circles poles measured in Q; crosses poles measured in R; all plotted on plane of section P.

Figure 18. Edges $[e:r] = [r:r']$ in 324 lamellae measured in sections P (188) and Q (136), and plotted on P. Contours at 2%, 1% and 0.3%.

Figure 19. Edges $[e:r] = [r:r']$ in 242 lamellae in R. Contours at 4%, 2%, 0.4%.

It is therefore concluded that for the rock as a whole the horizontal crystal axes of the calcite grains have random orientation, but that there may possibly be very local fields of weak orientation within the individual thin sections. The only significant preferred orientation of the calcite lattice is the E.-W. alinement of optic axes. The girdle pattern of the visible deformation lamellae and the slight concentration of their edges (intersections with {0001}) in a southward-dipping direction are directly correlated phenomena attributed to selective development of deformation lamellae. That this selection of certain $\{01\bar{1}2\}$ planes and omission of others was controlled by their respective orientations in space, is shown by the fact that the visible lamellae conform to a uniform pattern recognizable in all three sections.

Preferred orientation of edges $[e:r] = [r:r']$. The edge between the twinning plane $(01\bar{1}2)$ and either of the adjoining unit rhombohedrons $(01\bar{1}1)$ or $(\bar{1}101)$ is the glide line for twin gliding on $(01\bar{1}2)$. Orientation diagrams for this direction within visible deformation lamellae are reproduced as figures 18 (sections P and Q) and 19 (Section R). The general lack of preferred orientation is remarkable. The only consistent feature seems to be a poorly defined broad sector of minimum concentration covering the S.-W.-D. quadrant.

Preferred orientation of edges $[e:e']$. The most consistent element in the fabric so far as deformation lamellae are concerned is a marked preferred orientation of the edges common to two visible lamellae in any given grain. We have already seen that about 50% of the measured grains show two sets of lamellae, and about 15% show three sets. Of those showing three, about one-half have two well developed sets of lamellae, and one poorly defined set which was excluded for present purposes. The collective diagram, figure 20, shows the orientation of 246 edges of the type $(01\bar{1}2):(1\bar{1}02)$ measured in all three sections. Approximately 70% of these represent grains with only two sets of lamellae; 15% are edges between well developed lamellae in grains which also show a weakly defined third set (here excluded); the remaining 15% are the mutual intersections of three equally prominent sets of lamellae in a small number of grains. The consistent feature common to all three elemental diagrams (figs. 21 to 23) and to the collective diagram (fig. 20) is a strong concentration of edges in the D.-S.-E. quadrant. In other words, there is a

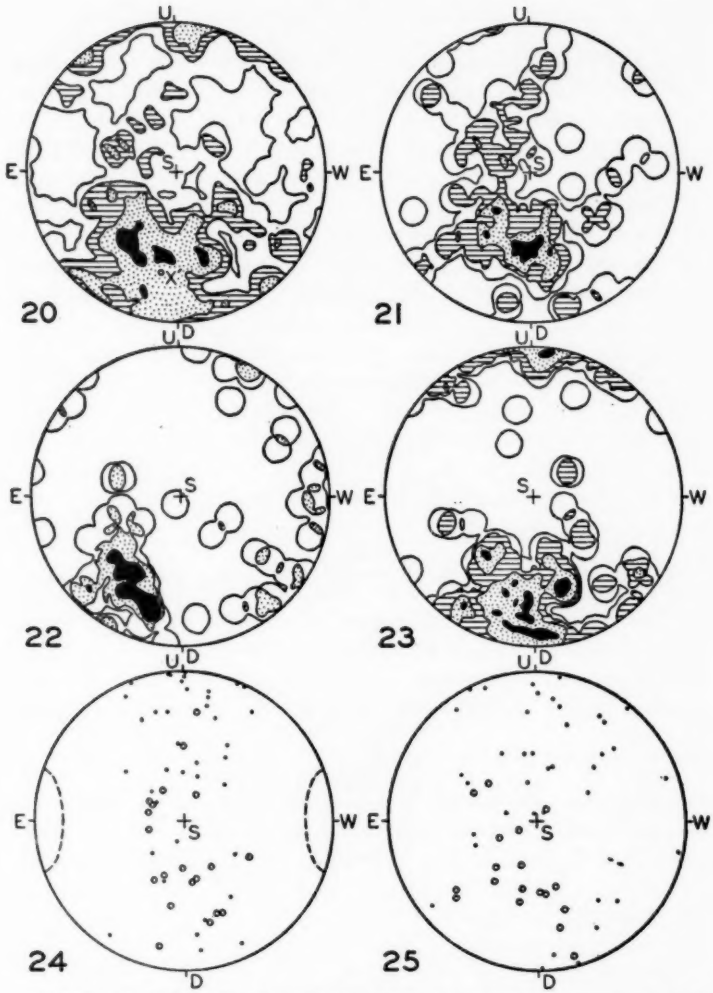

Figure 20. Edges [$e : e'$] for 246 pairs of e lamellae measured in P (90), Q (57) and R (99) and plotted on plane of P section. Contours at 4%, 2%, 1%, 0.4%, per 1% area.

Figure 21. [Edges [$e : e'$] for 90 pairs of e lamellae in section P. Contours at 7%, 4%, 2%, 1%.

Figure 22. Edges [$e : e'$] for 57 pairs of e lamellae measured in section Q and rotated into plane of section P. Contours at 7%, 4%, 2%.

Figure 23. Edges [$e : e'$] for 99 pairs of e lamellae, measured in section R and rotated in to plane of section P. Contours at 6%, 4%, 2%, 1%.

Figure 24. All three edges [$e : e'$] for 19 grains in P, with optic axes within 20° of E.W. horizontal direction (i.e., within the broken arcs). Open circles represent edges between observed pairs of lamellae.

Figure 25. All three edges [$e : e'$] for 20 grains selected at random in section P. Open circles represent edges between observed pairs of lamellae.

very pronounced tendency for the edges between intersecting deformation lamellae to dip steeply in a southerly to southeasterly direction, which is also the axis of the girdle in the lamellae diagram, figure 9. This tendency is so strong that it becomes obvious in any plot of ten or fifteen edges.

To test the possible influence of existing space-lattice orientation of grains upon the pattern of figure 20, all three edges of the type $(01\bar{1}2):(1\bar{1}02)$ were located and plotted for a selected group of 19 grains from section P, whose optic axes lie within 20° of the ideal E.-W. horizontal direction. For comparison, all three edges were also plotted for each grain in a random group (numbers 1 to 20) in the same section. Both diagrams (figs. 24, 25) show equally strong preference for edges between visible deformation lamellae to lie in the S.-D. rather than in the S.-U. sector. Pre-existing space-lattice orientation thus appears to have had no influence upon the pattern of figure 20.

Preferred orientation of $\frac{\perp [e:e']}{(0001)}$. The strong orientation of edges $[e:e']$ discussed in the previous section is accompanied by equally strong orientation of that line within {0001} which is perpendicular to $[e:e']$ the common edge between visible deformation lamellae. This crystallographic line is here designated $\frac{\perp [e:e']}{(0001)}$. Its state of preferred orientation is illustrated by the collective diagram figure 26 which is based upon perpendiculars drawn to all $[e:e']$ edges plotted in figure 20. The corresponding elemental diagrams for grains measured in section R (figs. 27, 28) bring out the same relationship.

The line $\frac{\perp [e:e']}{(0001)}$ is also one of the three horizontal crystal axes. For example, in a grain showing two sets of deformation lamellae, $e = (01\bar{1}2)$ and $e' = (1\bar{1}02)$, the line $\frac{\perp [e:e']}{(0001)}$ coincides with the common edge between (0001) and the third rhombohedron plane $(\bar{1}012)$, i.e. with the crystal axis A_2. Figures 26 and 27 thus illustrate the state of preferred orientation of edges of the type $[e:c]$ for those $\{01\bar{1}2\}$ faces which have remained inactive during deformation of the rock. It is interesting to compare figure 27 with figure

15, which shows the orientation of edges $[e:c]$ for active $\{01\bar{1}2\}$ lamellae in the same section (R).

Preferred orientation of directions within twin lamellae $\{01\bar{1}2\}$. Measurements to be described in this section were made with a view to determining the relative parts played by

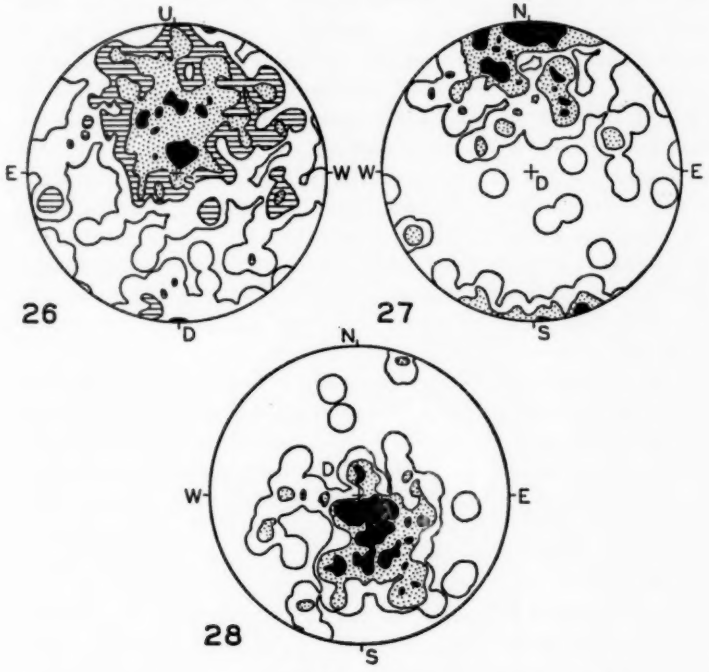

Figure 26. Direction $\frac{\perp [e:e']}{(0001)}$ for 246 pairs of lamellae measured in P (90) Q (57) and R (99) sections and plotted on plane of P section. Contours at 4%, 2%, 1%, 0.4%, per 1% area.

Figure 27. Direction $\frac{\perp [e:e']}{(0001)}$ for 99 pairs of lamellae in section R. Contours at 5%, 3%, 1%.

Figure 28. Edges $[e:e']$ for 99 pairs of lamellae in section R. Contours at 5%, 3%, 1%.

twin gliding and translation gliding in the origin of visible deformation lamellae. Poles of optic axes and lamellae were plotted separately for grains in which the twinned nature of at least one lamella could be recognized with certainty. This was the case for only 50 grains (58 sets of twinned lamellae)

out of the total 340 grains (571 sets of lamellae) measured. Measurements were also made on 15 additional grains with unusually clear twinning (18 sets of lamellae) in Section R.

Figures 29 and 30, respectively, show the orientation of optic axes in the main untwinned portions of the 65 grains concerned, and the poles of the 76 sets of definite twin lamellae developed in these grains. Comparison with figures 5 and 9 shows that undoubted twinning is restricted to grains with a rather narrow range of orientation. Twinning seems to show a marked preference for grains whose optic axes lie in the lower half of the orientation diagram, i.e. dip gently downward, somewhat to the south of the ideal E.-W. direction which corresponds to the maximum of figure 5. The lamellae themselves are concentrated asymmetrically in the two S.-W. quadrants of figure 30, leaving the S.-E. quadrants almost unoccupied. The corresponding glide lines $[r : r']$ shown in figure 31, like those of figure 18, show no obvious regularity of orientation.

The space-lattice within the newly twinned lamellae is even more sharply oriented, as indicated by figure 32 (optic axes within 76 sets of twin lamellae). Notable features of this orientation pattern, equally apparent in all three corresponding elemental diagrams for P Q and R sections respectively, are the strong concentration of poles in the U.-S.-W. quadrant and the complementary unoccupied area in the D.-S.-W. quadrant. It is interesting to compare figure 32 with figures 33 and 34. The latter show the orientation of optic axes within all observed deformation lamellae on the assumption that these are the result of twinning. They faintly resemble figure 32 in that they show a weak maximum in the U.-S.-W. (= D.-N.-E.) quadrant. The implications of this contrast will be discussed later; but in the meantime, it may be noted as evidence in general support of the hypothesis that twinning was not involved in the formation of a high proportion of visible deformation lamellae in Yule marble.

INTERPRETATION OF PREFERRED ORIENTATION PHENOMENA IN YULE MARBLE

Nature and origin of space-lattice orientation of calcite. The space-lattice orientation of calcite in Yule marble conforms to a simple pattern. The *c* axes tend to lie at high angles to the plane of foliation which itself is defined by dimensional

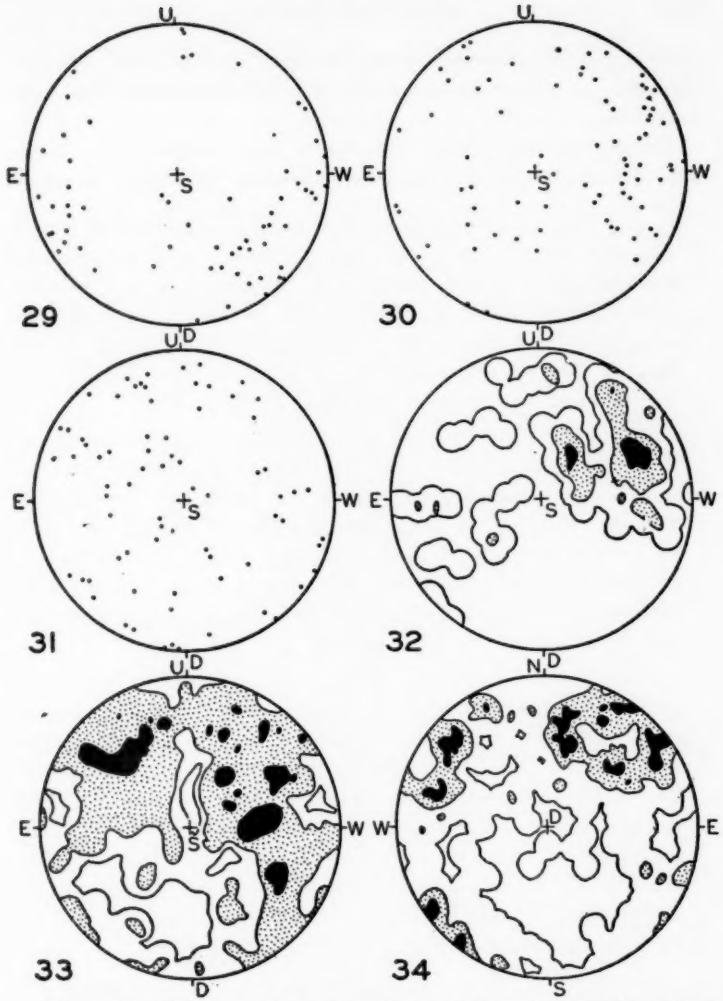

Figure 29. Optic axes in main portions of 65 grains showing at least one set of definite twin lamellae e; measured in P, Q, and R sections and plotted on plane of P section.

Figure 30. Poles of 76 definite twin lamellae e in 65 grains of figure 29.

Figure 31. Edges $[e:r] = [r:r']$ for 76 definite twin lamellae e in 65 grains of figures 29 and 30.

Figure 32. Optic axes [0001] in 76 definite twin lamellae e of figure 30; measured in P (24), Q (26) and R (26), and plotted on plane of P section. Contours at 7%, 4%, 1.3%.

Figure 33. Optic axes [0001] in 324 observed lamellae e, assuming twinning for each set of lamellae; measured in P (188) and Q (136) and plotted on plane of P section. Contours at 2%, 1%, 0.3%.

Figure 34. Optic axes [0001] in 247 observed lamellae e of section R, assuming twinning for each set of lamellae. Contours at 3%, 2%, 0.4%.

parallelism of somewhat lenticular grains. Preferred orientation of no other direction in the calcite lattice has been detected.

Orientation of calcite with the *c* axes normal to a single set of visible *s*-planes has been explained in several ways:—

(1) The experimental work of Griggs showed that simple compression of dry marble can produce a very pronounced orientation of *c* axes parallel to the direction of compression (Griggs, 1940, p. 1006, fig. 2). With this is associated equally strong preferred orientation of $\{01\bar{1}2\}$ twin lamellae, in planes symmetrically inclined at 65°-70° to the direction of compression (Griggs, 1936, p. 568).

(2) Fairbairn (1941b, pp. 629-631) has drawn attention to the possibility that translation on {0001} may be an effective orienting mechanism for dolomite. Conceivably the same mechanism might be possible for calcite, in which case the *c* axes would show preferred orientation normal to to s-planes of slip, and the glide line (= one of the three horizontal crystal axes) should be oriented parallel to the slip direction within the *s*-planes.

(3) In growth fabrics calcite may crystallize as tabular grains elongated at right angles to the *c* crystal axes and parallel to the direction of greatest ease of growth in the rock fabric (Sander, 1930, p. 206; Reed, 1945, p. 384). The state of orientation observed in Yule marble thus could possibly be due to mimetic preservation of pre-existing *s*-surfaces by post-tectonic recrystallization. Felkel (1929, pp. 62, 63) has described cases where recrystallized grains in deformed marble have their optic axes alined parallel to *s*-planes developed during preceding deformation.

(4) Finally there is the possibility that orienting of calcite is the result of recrystallization (indirect componental movement) of the rock under simple compression. Such a mechanism would explain the fabric developed in the preliminary experiment of Griggs (1940, p. 1007) on compression of marble at 150°C. in the presence of carbonated water. It is also advocated by Bain (1938, pp. 17, 18) who draws attention to the maximum compressibility and minimum solubility of calcite parallel to the *c* axis as factors possibly to be correlated with the orienting process.

In the case of Yule marble, the first two mechanisms listed above are rendered unlikely by the total lack of preferred orientation of lattice directions other than the *c* axis. However, the fabric data are compatible with orienting by crystallization. This could involve either selective growth of suitably oriented grains under the direct influence of compression normal to the foliation, or post-tectonic crystallization controlled by a pre-existing set of *s*-planes of undertermined origin.

Orientation of deformation lamellae. The visible deformation lamellae in Yule marble conform to a pattern which seems constant throughout the field of the investigated block. Its main features are as follows:

(1) Poles of lamellae, while necessarily concentrated in the vicinity of the direction of alinement of optic axes, also show a distinct though rather weak girdle, the axis of which (X in fig. 9) dips S. 30° E. at almost 35°.

(2) Where only two sets of lamellae are well developed in each grain (over 70° of the total number), the intersection $[e : e']$ of lamellae in any grain tends to be oriented parallel to the axis of the lamellae girdle (cf. fig. 20).

(3) There is equally strong orientation of the normal to $[e : e']$ within {0001}, around a corresponding direction in the lamellae girdle (cf. fig. 26).

(4) The glide line $[r : r']$ for twinning on $\{01\bar{1}2\}$ has random orientation (cf. fig. 18).

The distinctive lamellae pattern contrasts with, and cannot be directly related to the simple space-lattice orientation pattern discussed in the previous section. A reasonable explanation is that the lamellae pattern has been imprinted by late deformation upon a rock fabric which already possessed strong space-lattice orientation of the calcite grains. According to this view the lamellae developed wherever glide planes and directions were favorably oriented with regard to the deforming stresses.

It is instructive to compare the orientation of lamellae in Yule marble with corresponding data recorded by Felkel (1929) in her classic account of the fabric of calcareous tectonites from the Austrian Alps. This author, as well as measuring *c* axes and $\{01\bar{1}2\}$ lamellae, has recorded the orientations of such crystal directions as the glide line $[r : r']$ in $\{01\bar{1}2\}$, and the two bisectors of the angles between the two

glide directions in such grains as show two sets of lamellae. The rocks in question include marbles with a single set of *s*-planes of slip, other rocks with several such *s*-planes intersecting in a B-axis, and yet others with a foliation developed by flattening. Some of Felkel's observations which may bear on the case of Yule marble are as follows:

(1) In rocks where there is a single set of *s*-surfaces (= *ab*) of slip, with corresponding strong concentration of lamellae parallel to *ab*, there is usually a distinct concentration of glide lines $[r : r']$ parallel to the *a* fabric axis; but these directions also spread from *a* into a continuous *ab* girdle (Felkel, 1929, figs. 10, 11). In B-tectonites in which the poles of lamellae are distributed through a B-girdle, orientation of glide lines $[r : r']$ is poor, the only regular feature being a broad irregular girdle more or less parallel to the foliation.

(2) Directions which nearly always show sharp orientation are the lines bisecting the angles between two $\{01\bar{1}2\}$ lamellae in any grain. The acute bisector, *Rsyk*, is the same direction as is designated $\frac{\perp [e : e']}{(0001)}$ in this paper. The obtuse bisector *Rsyg*, is a direction intermediate between the *c* axis and $[e : e']$ in any grain. There seem to be two alternative rules for orientation:—

(a) *Rsyg* is concentrated in the vicinity of the *a* fabric axis (Felkel, 1929, figs. 13, 29); *Rsyk* = $\frac{\perp [e : e']}{(0001)}$ is rather irregularly concentrated in the general vicinity of *b* (Felkel, 1929, figs 14, 28). The rocks in question are either S-tectonites with one of slip surfaces, or B-tectonites with intersecting sets of slip surfaces.

(b) *Rsyk* = $\frac{\perp [e : e']}{(0001)}$ is strongly concentrated parallel or close to the *a* fabric axis (Felkel, 1929, fig. 39). The example described is a rock with foliation of the flattened type with paired slip planes symmetrically inclined to the foliation. Alinement of *Rsyk* parallel to *a* and of *Rsyg* parallel to *b* (B) seems also to be indicated in the case of a B-tectonite believed by Felkel to be complicated by the presence of an incipient second B-axis (Felkel, 1929, 74-76, figs. 57, 58).

In the light of Felkel's data it is possible to identify tentatively the three fabric axes with which to correlate the deformation lamellae in Yule marble. The axis b' (X in fig. 9) is located approximately as the axis of the lamellae girdle, figure 9. The maximum concentration of edges $[e : e']$ in figure 20 coincides roughly with b' of the lamellae diagram; so that in Yule marble the second of Felkel's orientation rules, stated under paragraph (b) above, appears to hold good. The center of the broad maximum concentration area for $\frac{\perp [e : e']}{(0001)}$ defines the position of the a' fabric axis on this assumption. The $a'b'$ plane of the lamellae fabric thus approximates fairly closely to the foliation; but there is no correspondence between the b' axes for lamellae and the macroscopic lineation identified earlier as the b fabric axis.

Tectonic significance of the lamellae orientation pattern. At least some of the observed deformation lamellae must be of late origin. For example, many cases were observed where each lamella in one grain is matched by a similarly situated (but differently oriented) lamella continuing on across the immediately adjacent grain. Such lamellae can have formed only after both grains concerned had assumed their present orientation and outline.

The megascopic foliation is defined by parallel orientation of lensoid grains, and with it the space-lattice orientation of the calcite fabric is simply correlated. It is therefore likely that the observed space-lattice orientation, and the present orientation of grains according to external form developed simultaneously. The orientation pattern of the deformation lamellae has probably been influenced by the foliation; but it also shows clearly a girdle arrangement completely lacking in the space-lattice pattern. This condition, too, suggests a late origin for the lamellae. Moreover, the external shape of the elongated grains which dominate the foliation cannot be accounted for by movement on the observed lamellae within them. If it be assumed that lamellae are products of twin gliding, then in any lensoid grain the lamellae are too few and much too narrow to account for any perceptible elongation. If on the other hand the more effective mechanism of translation gliding is appealed to, the outline of a deformed grain should be notably offset wherever it is cut by a translation

lamella. Significant offsetting or stepping of grain boundaries, though searched for carefully, was not found.

The fabric characters outlined above are all compatible with the hypothesis, now put forward, that the deformation lamellae represent the imprint of a late, relatively weak deformation insufficient to modify perceptibly a pattern of space-lattice orientation and a related foliation which had already developed as described in an earlier section. It is not necessary to assume that all visible lamellae belong to the one period of deformation. Indeed there are at least three ways in which lamellae may have formed; and in all probability lamellae of all three modes of origin may be present:—

(1) Lamellae may be expected to form to some extent during grinding of the thin sections. In the present case the number of such lamellae cannot be great, since so many sets of lamellae conform in some way to a pattern of preferred orientation which is common to all three sections.

(2) By analogy with the behavior of metallic aggregates and alloys (cf. Boas and Honeycombe, 1946, 1947), the internal stresses set up by differential expansion and contraction of crystals of calcite (a highly anistotropic material), during the long process of cooling and unloading that preceded exposure of the rock at the earth's surface, may well have been relieved to some extent by local translation or twin gliding. If the lamellae pattern in Yule marble is an expression of this kind of internal adjustment, all its features should be simply related to two directions which might conceivably have exerted an orienting influence, viz. the direction of pre-existing alinement of optic axes normal to the foliation, and the vertical direction of the force of gravity. No such simple relation has been observed.

(3) There remains the third possibility that late tectonic deformation is responsible for the appearance of at least such lamellae as conform to the orientation pattern here recorded.

Mechanism of gliding. Although deformation lamellae are conventionally described as "twin lamellae" in most text-books of petrography, in some rocks the twinned condition of many lamellae is by no means obvious. In Yule marble the great majority of observed lamellae belong to this doubtful category. When tilted parallel to the vertical axis of the micro-

scope they appear as thin sharp lines resembling cleavage cracks rather than twin lamellae. If they are indeed twinned they cannot be distinguished from the host crystal by differences in optical behavior. There is an alternative possibility, namely, that many of these lamellae are due to translation gliding on $\{01\bar{1}2\}$, a mechanism experimentally demonstrated for single crystals of calcite by J. F. Bell (according to Fairbairn, 1942, p. 63). Both Felkel (1929, p. 79) and Sander (1930, p. 202) consider that pure translation, as well as twin gliding, on $\{01\bar{1}2\}$, is an important orienting mechanism.

Evidence strongly suggestive of translation gliding on $\{01\bar{1}2\}$ in the case of Yule marble is noted briefly as follows:—

(1) Definite twinning was recognized in only 10% of the 571 sets of lamellae measured in the course of this investigation.

(2) The glide line $[r : r']$ for twinning in $\{01\bar{1}2\}$ lacks any significant orientation in Yule marble (fig. 18). However this is perhaps mainly due to the weakness of the lamellae orientation pattern for the glide line $[r : r']$ seems likewise to lack preferred orientation even for cases of undoubted twinning (fig. 31). Moreover, the most likely glide line for translation in $\{01\bar{1}2\}$ is also $[r : r']$ (cf. Fairbairn, 1942, p. 63).

(3) Figures 29 and 30 show clearly that undoubted twinning is confined to grains having a range of space-lattice orientation which is narrowly limited when compared with that of the rock as a whole. Thus in figure 29, the optic axes of the host grains fall within the upper half of the diagram in only 25% of those cases where undoubted twinning occurs. A count of the plotted points (340) corresponding to figure 5 shows that the optic axes of all measured grains are evenly distributed, 50% in each half of the diagram. This strongly suggests that twinning, as contrasted with translation, occurs only in grains already having a favorable orientation of space-lattice. But it is also possible that all observed lamellae are twinned, and that twin gliding only proceeds far enough to develop relatively thick optically recognizable lamellae in grains with favorable orientation.

(4) Figure 32 shows that there is very strong preferred orientation of the optic axes within undoubted twin lamel-

lae. This diagram differs notably from those showing the orientation of optic axes in *all* lamellae on the assumption that these are indeed due to twinning (figs. 33, 34). The range of orientation in the latter is much broader than is the case for undoubted twin lamellae.

The case for translation gliding in Yule marble is still not definitely established. But the facts outlined are at least thoroughly compatible with the hypothesis that a high proportion, and perhaps even the great majority, of the deformation lamellae observed in this rock originated by translation gliding in $\{01\bar{1}2\}$. Strong preferred orientation of the directions $[e : e']$ and $\frac{\perp [e : e']}{(0001)}$ for paired lamellae suggests that the orientation of some potential glide line, as well as orientation of the plane $\{01\bar{1}2\}$, within the rock fabric has had some influence in determining whether or not gliding should take place on a given $\{01\bar{1}2\}$ plane in any given grain. By analogy with the cases of quartz (e.g. Fairbairn, 1941a; Ingerson and Tuttle, 1945) and olivine (Turner, 1942), preferred orientation of some glide line within the active glide plane is to be expected. Moreover, it is possible that translation on $\{01\bar{1}2\}$ may have been accompanied by translation on some other plane such as $\{0001\}$. Speculation beyond this point is not justified in the absence of any strict analysis of gliding possibilities in the calcite lattice, taking into account electrical properties of the component ions as well as their geometric arrangement in space.

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THE BASE OF THE CAMBRIAN IN THE SOUTHERN APPALACHIANS

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PART II

OCOEE SERIES

General relations.—For a distance of 60 miles or more southwest of the Virginia-Tennessee boundary the Chilhowee group lies directly on the Cranberry and other granites equivalent to the injection complex of Virginia (fig. 1). If any intervening sedimentary or volcanic rocks once existed here, they were removed prior to deposition of the Chilhowee group.

Southwest of this point, from the French Broad River through southeast Tennessee into northern Georgia, the Chilhowee group is flanked on the southeast by rocks of the Ocoee series, which form the Great Smoky Mountains and other high ranges on the Tennessee-North Carolina border. The stratigraphy and structure of this area is much less clear than that farther northeast, and is undoubtedly more complex. Extensive overthrusts are present, and low to high-grade metamorphic features are nearly everywhere evident.

The Ocoee series was named by Safford (1856, pp. 151-152; 1869, pp. 183-198) for the Ocoee River, Polk County, Tennessee.[9] From Safford's time to the present, the age, origin, and relations of the Ocoee have been much debated and variously interpreted. The principal interpretations that have been made are indicated in table 2.

Some of these interpretations have been outmoded by the acquisition of contrary evidence. Some represent successive interpretations by the same geologists—for example, interpretations 2, 3, and 5 are by Keith, and interpretations 6, 7, and 8 are by Stose and Stose. In this paper, it does not seem necessary to consider the evidence for or against all the interpretations. The only one that will be considered at length is the last one by Keith (interpretation 5, table 2), after which an alternative of the writer's (interpretation 10) will be proposed.

[9] Problems relating to usage of the term Ocoee series are discussed under the heading "Notes on terminology" at the end of this paper.

TABLE 2

Interpretations that have been made regarding age and relations of the Ocoee series

	Date	Author and reference	Age	Stratigraphic relations
1	1869	Safford, Geology of Tennessee	Potsdam group of Lower Silurian; also Eozoic	Lies stratigraphically beneath Chilhowee group; relations gradational.
2	1889 1891	Keith, unpublished work Willis, in Walcott, U. S. Geol. Survey Bull. 81, pp. 299-300	Ordovician or younger	Unconformable on Ordovician rocks of Appalachian Valley; clastic southeastern facies of upper Ordovician and younger Paleozoic rocks.
3	1895	Keith, Knoxville folio (number 16)	Age unknown	Ample evidence which separates it from the Cambrian series, though not sufficient to fix its age.
4	1895	Hayes, Cleveland folio (number 20)	Age unknown, probably Algonkian	Bears all the marks of extreme age so that it is best to consider it Algonkian until satisfactory evidence to contrary is found.
5	1904 1907	Keith, Asheville and Nantahala folios (numbers 116 and 143)	Lower Cambrian	In part lateral southeastern equivalent of Chilhowee group, in part older.
6	1932 1932 1936	Jonas, AM. JOUR. SCI., 5th ser., vol. 24, pp. 240-241. Geologic map of United States. Crickmay, Geol. Soc. Amer. Bull., vol. 47, p. 1391.	Partly Lower Cambrian, partly pre-Cambrian	Ocoee belt is divided longitudinally by Cartersville overthrust, masked by a zone of retrogressive metamorphism, which brings together two units of similar lithology but of very different age.
7	1944	Stose and Stose, AM. JOUR. SCI., vol. 242, p. 416.	Pre-Cambrian	Nearly everywhere separated from Chilhowee group to northwest by overthrust fault; probably unconformable below Chilhowee.
8	1946	Stose and Stose, Geol. Soc. Amer. Bull., vol. 57, p. 1233.	Partly Ordovician, partly pre-Cambrian	Shales, limestones and sandstones along northwest side of Ocoee belt are Ordovician, and separated by overthrust fault from remainder of Ocoee series.
9	1948	Lombard, Amer. Assoc. Petrol. Geol. Bull., vol. 32, p. 720.	Possibly Paleozoic	May be an allochthonous southeastern clastic facies of some or much of Paleozoic.
10	1949	King, this paper.	Later pre-Cambrian	Lies stratigraphically beneath Chilhowee group, but formed during an earlier cycle of sedimentation; possibly unconformable below Chilhowee, at least locally.

Interpretation by Keith.—Some of the interpretations indicated in table 2 imply a complete or nearly complete separation of the Ocoee series by faults from the Chilhowee group and other rocks of Paleozoic age to the northwest. Lombard (1948, p. 720; interpretation 9, table 2) thus suggests that the series may be an allochthonous southeastern facies of a considerable part of the Paleozoic. Stose and Stose (1944, p. 416; interpretation 7), while considering the series allochthonous, believed it to be of late pre-Cambrian age.

Keith, on the basis of his comprehensive field studies of the Ocoee series, concluded on the other hand, that the series was closely related to the Chilhowee group, and that the separation of the two by faulting was local and minor. This interpretation has been confirmed by the writer and his colleagues, who likewise conclude that the Ocoee series and Chilhowee group are not only contiguous but closely related units.

Rocks here regarded as a part of the Ocoee series were divided by Keith into a number of formations, but as the terminology varies from one folio report to another, the record is difficult for the uninitiated to follow. Terminology used in the oldest report, the Knoxville folio (Keith, 1895, pp. 2-3) represents a preliminary attempt at subdivision which was subsequently found unusable. The terminology used in the later folios, such as the Asheville (1904, pp. 4-6) and the Nantahala (1907, pp. 3-5) reflects Keith's more mature judgment, and applies to units that can be recognized in the field. It was also used by Keith in his unpublished work on the Mount Guyot, Cowee, and Murphy quadrangles. Some of the later terminology and interpretation was based on Keith's unpublished work in these three quadrangles, so that the evidence for it is not generally available to geologists.

Table 3 lists Keith's later classification and the earlier classification in the Knoxville folio. Correlations given between the two columns are only approximate.

According to Keith's later work, in the area northeast of the Great Smoky Mountains (Mount Guyot and Asheville quadrangles) the Cochran conglomerate of the Chilhowee group lies directly on the Hiwassee slate, which is well down in the column on table 3. In the Great Smoky Mountains, the Great Smoky conglomerate and the Nantahala slate are interpreted as overlying the Hiwassee slate. There is thus an excess

TABLE 3

Interpretation of sequence in Ocoee series according to Arthur Keith

	Keith, Asheville folio (1904), Nantahala folio (1907), and Mount Guyot sheet (unpublished)	Keith, Knoxville folio (1895)
	Overlying formations of the Murphy marble belt	(Top eroded)
Ocoee series	Nantahala slate	Clingmans conglomerate
		Hazel slate
	Great Smoky conglomerate	Thunderhead conglomerate
		Cades conglomerate
	Hiwassee slate	Pigeon slate
		Citico conglomerate
		Wilhite slate
	Snowbird formation	(Base concealed)
	Max Patch and Cranberry granites; Carolina gneiss	

of younger Ocoee-type rocks in the Great Smoky Mountains, as compared with the area to the northeast. This was explained by Keith by assuming that the Great Smoky conglomerate and Nantahala slate were equivalent to the Cochran conglomerate and Nichols shale of the Chilhowee group. Keith therefore believed that the Ocoee series was in part equivalent to the Chilhowee group, and was in part older. Throughout his later reports he therefore classed the formations belonging to the Ocoee series as of Lower Cambrian age.

This interpretation, while superficially plausible, fails to account for many features. The Great Smoky conglomerate is more than twice as thick as the Cochran conglomerate; moreover, it is of graywacke facies, whereas the Cochran is of arkosic and quartzose sandstone facies. These differences were supposed by Keith to result from lateral variations in the

deposit. To the writer, they appear so great that he does not believe the two formations could have been laid down in the same basin of deposition; hence it is unlikely that they are of the same age. Moreover, no such change from one facies to another has ever been traced out along the outcrop. In northeastern Tennessee the Unicoi formation (Cochran equivalent) crops out in successive outcrop belts, to a breadth of 35 miles across the strike, and the distance before deformation was probably twice as great. Variations in the Unicoi exist between

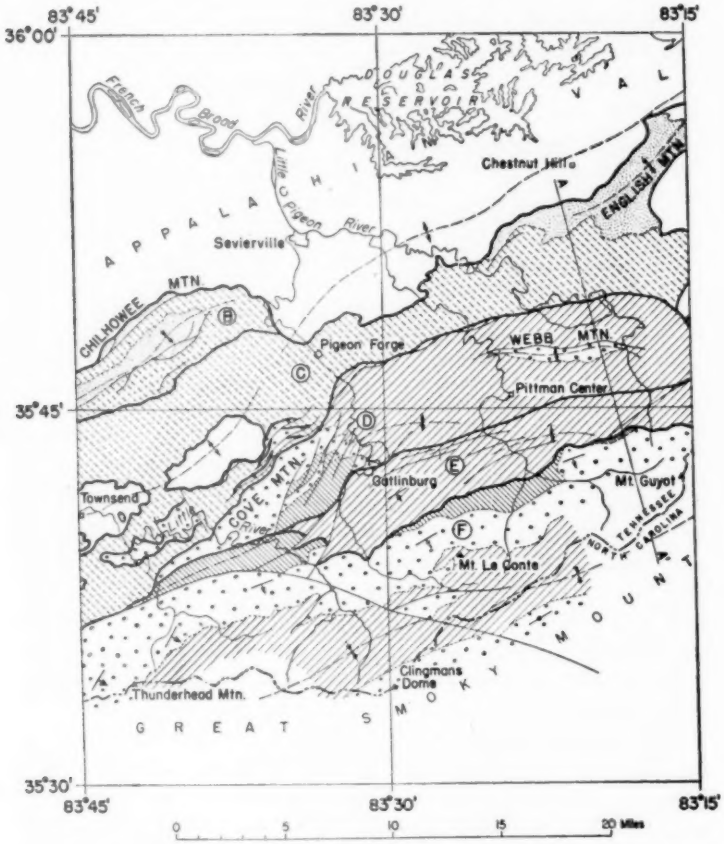
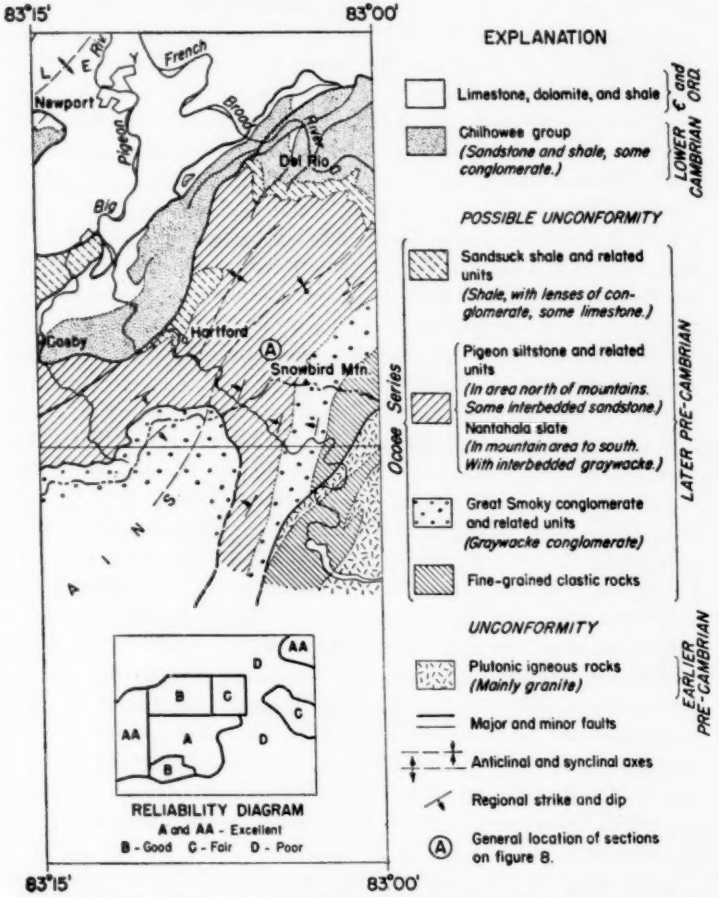


Figure 7. Preliminary geologic map of northeast part of Great Smoky Mountains and adjacent foothills to north, based on detailed and reconnaissance surveys by J. B. Hadley, H. W. Ferguson, and the writer.

the different outcrop belts, but the rocks remain recognizably Unicoi, and never assume a Great Smoky aspect. Moreover, it is highly unlikely that the beds beneath the Cochran and Great Smoky are the same, although each were termed Hiwassee by Keith. The formation beneath the Cochran is an argillaceous shale, with beds of conglomerate and limestone; the formation beneath the Great Smoky is siltstone, with beds of fine-grained graywacke sandstone.



Regional interpretations of the stratigraphy and structure are those of the writer. The geology in areas marked AA on the "reliability diagram" is published with permission of the Tennessee Division of Geology.

Tentative interpretation by the writer.—Work on the Ocoee series in Great Smoky Mountains National Park is now in progress by parties of the U. S. Geological Survey and Tennessee Division of Geology. On the basis of detailed and reconnaissance work by these parties, the writer has arrived at a tentative interpretation of the sequence which differs from that of Keith (interpretation 10, table 2). This is briefly outlined here, and is illustrated by a map (fig. 7) and by stratigraphic sections (fig. 8). Final interpretation of the Ocoee series must await further field work by the present parties, and this work will no doubt result in more or less modification of the interpretation here given.

The beds beneath the Cochran conglomerate northeast of the Great Smoky Mountains (the so-called Snowbird formation and Hiwassee slate) are believed to be equivalent to the entire Ocoee series farther southwest, rather than its lower part alone. To the northeast these beds are relatively thin, but to the southwest, near the Big Pigeon River, they attain a thickness of about 17,500 feet (section A, fig. 8). The shales at the top, the so-called Hiwassee, are similar in character to the Sandsuck shale, a formation which underlies the Cochran conglomerate of the Chilhowee group in its type area on Chilhowee Mountain (Section B, fig. 8). The Sandsuck shale is believed to be the top formation of the Ocoee series, and to be younger than any rocks in the Great Smoky Mountains to the southeast. The strata which were correlated with it by Keith, and which were supposed to underlie the Great Smoky conglomerate of the mountains, are actually much older (section E, fig. 8). The formations in the Great Smoky Mountains are believed to be equivalent to parts of the so-called Snowbird formation near the Big Pigeon River, and to have been raised successively higher toward the southeast by thrust faults (structure section A, fig. 9). For example the Great Smoky conglomerate (section F, fig. 8) is probably equivalent to conglomeratic beds in the lower part of the Snowbird formation on the Big Pigeon River. According to this tentative interpretation, the sequence of the Ocoee series is therefore as shown in table 4.

According to this proposed interpretation, the Ocoee series underlies the Chilhowee group, is entirely older than the Chilhowee group, and no part of either unit is equivalent to any

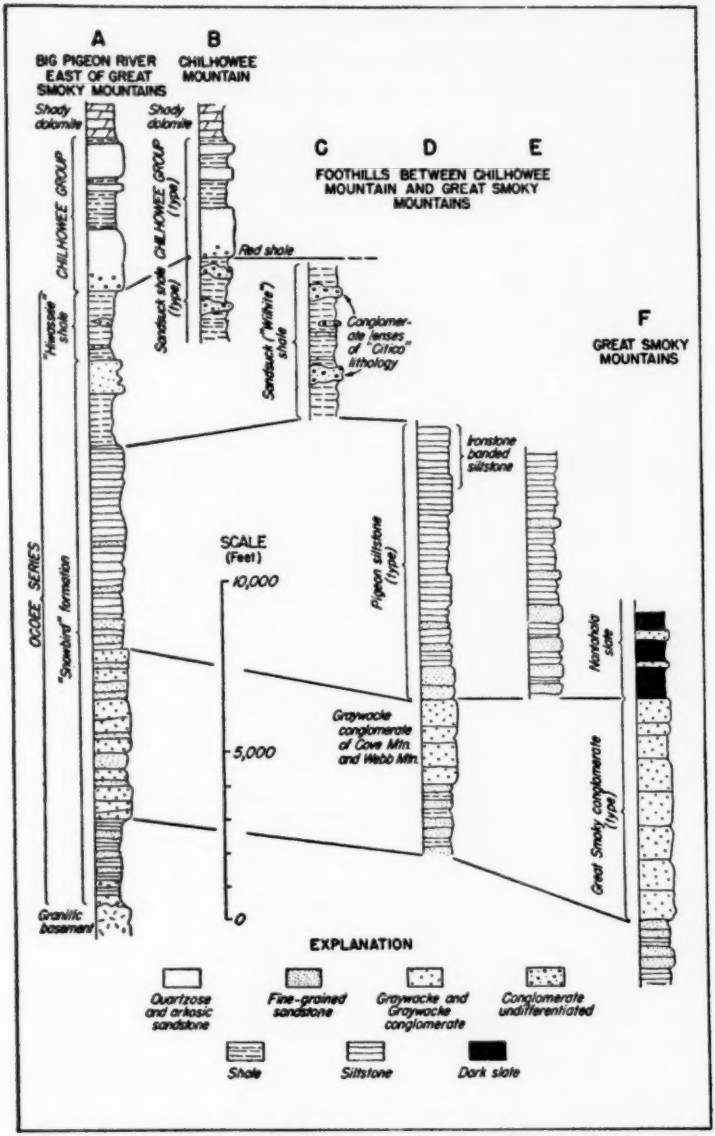


Figure 8. Preliminary stratigraphic sections of Ocoee series in northeast part of Great Smoky Mountains and adjacent foothills to north, to illustrate tentative interpretation by the writer. Location of sections is shown in figure 7. Sections A and B are based mainly on work of H. W. Ferguson, and are published with permission of the Tennessee Division of Geology.

part of the other. The Ocoee is a distinct series of great thickness, characterized by its own sequence and its own lithologic features.

Basement on which series was deposited.—The Ocoee series contains great quantities of material derived from preexisting plutonic rocks, including much "blue" quartz like that in the

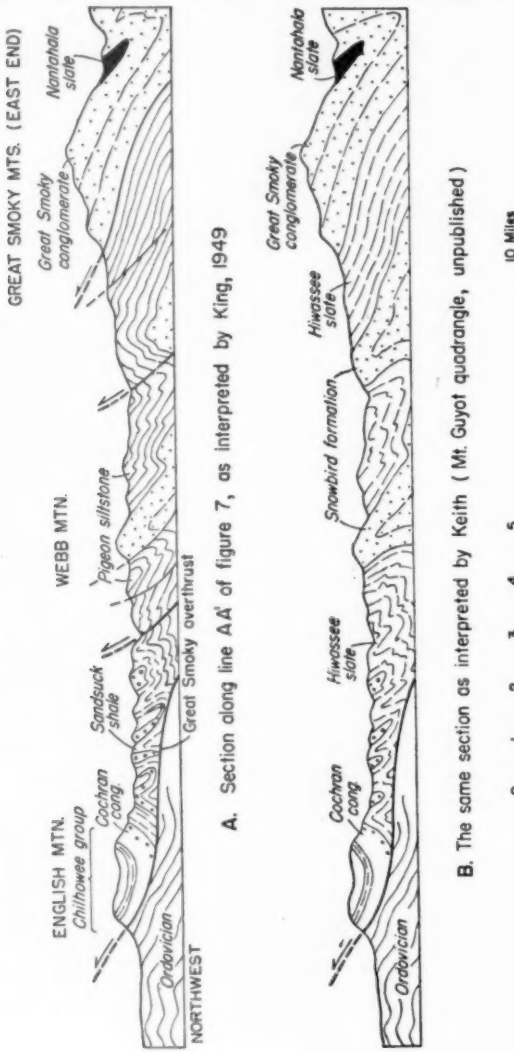


Figure 9. Structure sections along line A A' of geologic map, figure 7, showing interpretations by the writer, and by Keith.

TABLE 4

Tentative interpretation of sequence in Ocoee series in northeast part of Great Smoky Mountains, as proposed by P. B. King

Unit	Representative formations included in unit	Character	Approximate thickness (in feet)
	Chilhowee group at top of sequence (Cochran conglomerate is lowest formation).		
4	Sandsuck shale	Argillaceous shale, with interbedded layers and lenses of limestone and of conglomerate (latter is the Citico conglomerate of Keith's early reports).	4,000
3	Pigeon siltstone (north of mountains) Nantahala slate (in mountain area)	North of mountains, laminated siltstone and interbedded fine-grained graywacke sandstone. In mountain area, dark gray or black slate, with interbedded coarse graywacke.	8,000
2	Great Smoky conglomerate	Medium to coarse graywacke sandstone and conglomerate, composed of quartz and feldspar grains, in thick beds, with graded bedding.	6,000
1		Fine-grained sandstone, with interbedded siltstone and slate.	2,500
	Base not exposed in Great Smoky Mountains; equivalent beds near Big Pigeon River rest on Max Patch and Cranberry granites.		

Max Patch and Cranberry granites of the Asheville quadrangle, North Carolina (Keith, 1904, pp. 3-4). In the Asheville quadrangle, Keith mapped the Snowbird formation of the Ocoee series as lying unconformably on these granites. Reconnaissance observations by the writer and his colleagues suggest that this relation is probably correct, although in places there are structural complications at the contact.

On Cohutta Mountain, east of Chatsworth, Murray County, Georgia, Furcron and Teague (1947, pp. 19-21, pl. 1) have found that older granites and gneisses are exposed in a narrow strip along the northwest margin of the belt of outcrop of the Ocoee series, and they believe that the series lies unconformably on the granites and gneisses (fig. 10).

In other places, the basal relations of the Ocoee series are less certain. In the Nantahala quadrangle, North Carolina (Keith, 1907) and the Ellijay quadrangle, Georgia (La Forge and Phalen, 1913) the Ocoee series is mapped as lying unconformably on the Carolina gneiss, classed by Keith as of Archean age. Crickmay (1936, pp. 1380-1381) and others

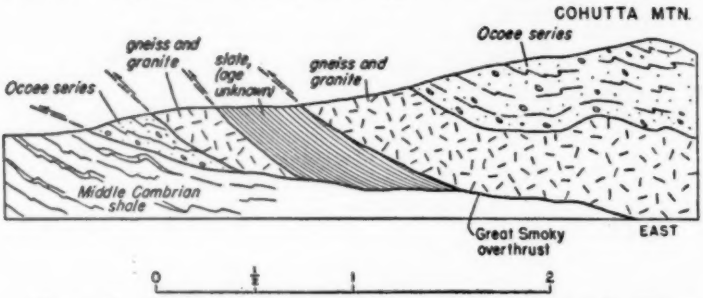


Figure 10. Section of Cohutta Mountain, east of Chatsworth, Murray County, Georgia, showing relation of Ocoee series to older granites and gneisses. After Furcron and Teague, 1947.

have expressed doubt as to this interpretation, and have pointed out that the more highly metamorphosed phases of the Ocoee closely resemble the Carolina gneiss. This suggests that the one is perhaps merely a greatly metamorphosed facies of the other. In western North Carolina, in the Mount Guyot and Cowee quadrangles, Keith (unpublished reports) mapped granites which were supposed to be pre-Ocoee, and against which the Ocoee series was supposed to overlap unconformably. These granites are definitely intrusive into the Ocoee (J. B. Hadley, personal communication, 1948).

Conditions of deposition.—The Ocoee series consists entirely of sedimentary rocks all of which are clastic, except for rare thin beds of limestone; no volcanic rocks are known. The Ocoee forms a tremendously thick mass. Keith reports thickness of 7,500 to more than 10,000 feet in the Knoxville and Nantahala quadrangles (1895, 1907), but these are certainly underestimates. As indicated by table 4, the thickness may exceed 20,000 feet, and the series thus has a mass nearly equal to that of the Paleozoic rocks in the Appalachian Valley to the northwest.

The sedimentary rocks of the Ocoee series form a distinctive suite, quite unlike those of other nearby clastic units, such as

the Chilhowee group. Some of the differences between the Ocoee series and the rocks of the Chilhowee group have been listed by Stose and Stose (1944, pp. 404-405). The lithologic, petrographic, and chemical character of the rocks of the Ocoee series have been described by Moneymaker (1938). Conditions of deposition of the Ocoee series have been outlined by Barrell (1925, pp. 15-20), although his conclusions must be modified to the extent that he accepted Keith's interpretation of the intergradation of the Ocoee series and the Chilhowee group.

The rocks of the lower part of the Ocoee series (unit 2, table 4) are of graywacke facies[10] and strongly resemble the graywackes of the Archean of the Canadian shield as described by Pettijohn (1943, pp. 941-960). Various textures occur, ranging from fine and medium-grained sandstones (in unit 3, table 4) to fine-grained conglomerates (unit 2), but there are no quartzose or arkosic sandstones like those in the Chilhowee group. The graywackes contain many grains of feldspar and quartz, but the matrix is argillaceous material, now altered to sericite and chlorite. The conglomerates contain few pebbles larger than half an inch in diameter, and practically all are single mineral grains or crystals, as though they had been derived from wholesale granular disintegration of the source rocks. Barrell (1925, p. 19) has noted that Ocoee rocks are characteristically gray, bluish gray, or even black-colored, implying rapid sedimentation and lack of thorough oxidation before burial.

In the graywackes of the Ocoee series, as in others, graded bedding is a striking feature, which suggests that the sediments were deposited rapidly, without sorting except that which was produced by settling in water. This is manifested by cyclical arrangement of the coarse and fine deposits, each cycle beginning with granular or pebbly deposits, followed by sandy and then silty or slaty deposits, the whole cycle being represented by beds a foot to more than 25 feet thick, and endlessly repeated through thousands of feet of section. In many places the slaty or silty beds at the tops of the layers are broken up and reincorporated as chips or slabs in the basal deposits of the succeeding unit. Ripple marks and cross bedding are rare. Pettijohn notes that these two features seem to be caused by

[10] For explanation of rock names used, see "Notes on terminology" at end of paper.

different conditions of sedimentation from graded bedding, and that they are seldom found together.

The succeeding beds (units 3, table 4) north of the mountains are largely siltstone, which forms a very thick and uniform body. This rock type, intermediate in texture between a sandstone and a shale, is relatively uncommon in nearby geological sequences, such as that of the Paleozoic rocks of the Appalachian Valley, where less rapid sedimentation permitted more thorough sorting of the constituents. A change to more normal conditions of sedimentation takes place in the final unit of the Ocoee series (unit 4, table 4), which contains beds of limestone, and whose shales and conglomerates are not unlike those in the succeeding Chilhowee group. The conglomerates of the final unit are not of graywacke facies, as are those in the lower part of the series. They were probably laid down under different conditions and derived from another source.

Whether the Ocoee series is unconformable below the Chilhowee group is as yet undetermined. Apparently no formations of the Ocoee series were cut out by erosion before Chilhowee time, and the Sandsuck shale (unit 4) forms the top at all places. Some evidence has been found by H. W. Ferguson (personal communication, 1949) that the Sandsuck beds were at least moderately eroded before Chilhowee time, but the significance of this remains to be evaluated.

Regardless of whether or not the Ocoee series and Chilhowee group are unconformable, the two units were laid down under different conditions, and during separate cycles of sedimentation. The sediments of the Ocoee series were deposited rapidly, in a region of high relief and great tectonic instability, in a relatively narrow, rapidly subsiding trough—a eugeosyncline. The sequence begins with coarse clastic deposits (units 1 and 2, table 4), whose source rocks in surrounding lands wasted by granular disintegration, and which were deposited before complete oxidation and with no sorting except that produced by settling in water. These are succeeded by silty sediments, laid down to a vast thickness, and finally by argillaceous sediments, which contain beds of limestone. Chilhowee time again begins with the deposition of coarse clastic deposits, but these are of arkosic and quartzose sandstone facies, and are the initial deposits of the Appalachian miogeosyncline of Paleozoic time.

GEOLOGIC HISTORY

This survey of the stratigraphy of the older Cambrian and the pre-Cambrian rocks of the southern Appalachians suggests the following possible events in the geologic history:

1) Prolonged erosion of a plutonic terrane, composed of such rocks as the Max Patch and Cranberry granites in Tennessee, and the injection complex in Virginia.

2) Deposition in restricted basins of sedimentary and volcanic rocks, including (a) the Catoctin greenstone and underlying sedimentary rocks, (b) the volcanics of the Mount Rogers area, and (c) the Ocoee series. All were formed under conditions of considerable crustal instability, manifested in the first two units by volcanic action and in the third by the development of a rapidly subsiding trough bordered by lands of high relief, a eugeosyncline. The origin and history of this crustal instability does not concern us directly here, except to say that it took place before the depositions of the Chilhowee group.

3) Remnants of the deposits of these basins are now widely separated from each other, the Chilhowee group in the intervening areas lying directly on the older plutonic rocks. This separation results either from removal of the original connecting strata from between the basins, from original isolation of the basins, or from both. No evidence exists to indicate whether deposition in the basins took place at the same or at different times. Very possibly the rocks of the different basins were not contemporaneous, yet they cannot be far apart in age.

4) Tilting of the margins of the basins during and at the close of the period of deposition, and erosion and truncation of the edges of the tilted beds. Such features have been seen by the writer at the edge of the Catoctin greenstone in the Elkton area and at the edge of the volcanics of the Mount Rogers area. An unconformity may also separate the Ocoee series from the Chilhowee group.

5) Deposition of the Chilhowee group as the initial deposit of the Appalachian miogeosyncline. The earliest deposits of the Chilhowee seem to be those which form the lower part of the Unicoi formation of northeast Tennessee and they may pass out by overlap in adjoining areas. In northern Virginia, at least, the time of their deposition is represented by a hiatus.

6) At intervals during early Chilhowee time there was renewal of volcanic activity. In northeast Tennessee, the main volcanic episode took place some time after the beginning of deposition of the Unicoi formation; consequently this volcanic episode took place at a much later time than the eruption of the volcanics of the Mount Rogers area. It is suggested that the volcanics of the Loudoun formation of northern Virginia are similarly much younger than those of the underlying Catoctin.

7) The first indications of life appear in upper Chilhowee rocks, the oldest being worm tubes of the *Scolithus* type. Trilobites and brachiopods do not appear until near the top of the Chilhowee group. The occurrence of these evidences of life in rocks of the Chilhowee group does not seem to be the result of abrupt evolutionary development, but may result from migration of marine life into a gradually improving environment.

8) Deposition of succeeding fossiliferous formations of Lower Cambrian age, beginning with the Shady and Tomstown dolomites.

CONCLUSIONS

The facts and interpretations just summarized suggest the following tentative conclusions as to the position of the base of the Cambrian in the southern Appalachians:

Proposals by the Cambrian subcommittee (Howell and others, 1944), and by Wheeler (1947) and Snyder (1947), to restrict the base of the Cambrian to the lowest horizon or formation that contains diagnostic Cambrian fossils have the virtue of precision, but seem unnecessarily restricted and arbitrary. Use of the base of the lowest formation that contains Cambrian fossils as a boundary is impracticable when one considers that formation boundaries in conformable sequences of beds are merely arbitrary units of mapping. The Erwin quartzite, for example, as it is traced southwestward, is divided into three formations. If the base of the Erwin is termed the base of the Cambrian, the boundary must be jogged upward where the division takes place, either to the base of the Murray shale or the base of the Hesse quartzite, depending on which contains the lowest fossil horizon. The use of the lowest horizon to contain diagnostic fossils has more to recommend it, but this depends largely on accidents of collecting. Thus, at one locality fossils are reported from the Murray shale; elsewhere the low-

est fossil horizon is found at the top of the overlying Hesse or its equivalents. Possibly the most definitive boundary between Cambrian and pre-Cambrian would be a fossil zone with a distinctive assemblage of fossils, even if occasional fossils should occur beneath.

Such a definition might be highly satisfying for precise paleontological zonation, yet would be unsatisfying to the general geologist and stratigrapher who must deal with such rocks in the field. Except for the fact that the highest part of the Chilhowee group is fossiliferous and the remainder unfossiliferous, it is a closely knit sequence of deposits laid down in conformable succession, with none of its parts greatly different in age from the other parts. Under the circumstances it would seem to be impracticable to term one part Cambrian and another pre-Cambrian. The supposed pre-Cambrian part is the logical beginning of the supposed Cambrian part.

On the other hand, the writer can agree with Snyder (1947, p. 152) as to the undesirability of the practice of extending the Cambrian downward through great thicknesses of unfossiliferous strata until a major unconformity is reached. Major unconformities, with subaerial or subaqueous deposits lying on plutonic rocks, such as those described by Bloomer and Bloomer (1947, p. 95) below the Oronoco formation in Virginia, and by Furcron and Teague (1947, p. 20) below the Ocoee series in Georgia, are undoubtedly significant mileposts in geologic history. They do not, however, necessarily mark the base of the Cambrian. Similar major unconformities between strata recognized by all to be pre-Cambrian are well known in the Lake Superior region, the Grand Canyon district, and elsewhere.

Conditions could conceivably exist where the fossiliferous Cambrian was separated from the next major unconformity beneath by a vast thickness of unfossiliferous sediments, with a gradual transition downward from distinctly Cambrian-like rocks to distinctly non-Cambrian-like rocks. Such a condition in southern Nevada is described by Wheeler (1947, pp. 155-157). In the writer's opinion, these conditions do not exist in the southern Appalachians. Cambrian-like rocks are underlain by non-Cambrian-like rocks, but the first are separated from the second by changes in sedimentation, and in part at least by unconformities that involve tilting, rearrange-

ment of the basins of deposition, and a moderate time hiatus. The extent of the basins of deposition and the environments of sedimentation were very different in each.

The writer concludes that the base of the Cambrian in the southern Appalachians can logically be placed at the base of the Chilhowee group, and that this group and its component formations forms the lowest unit of the Lower Cambrian series. He believes that the Catoctin greenstone and underlying sedimentary rocks, the volcanics of the Mount Rogers area, and the Ocoee series are probably of late pre-Cambrian age, although they may not necessarily be entirely contemporaneous.

NOTES ON TERMINOLOGY

Stratigraphic names.—The *Catoctin greenstone* was named by Keith (1894, p. 306), who called it the Catoctin schist. Most of the formation is not true schist and much of it is relatively massive. It has been termed a metabasalt in many geologic reports, but Bloomer and Bloomer (1947, p. 97) term it a propylite and interpret it as an altered andesite. As opinions differ regarding its precise petrographic classification, and as it may vary in composition from place to place, it seems most appropriate to use for it the general rock term greenstone, which was employed on the geologic map of Virginia (1928).

The *Ocoee series* was named by Safford (1856, pp. 151-152; 1869, pp. 183-198). Keith, in his subsequent folio work in the area did not use the term and preferred to speak of the sequence in terms of the component formations. However, the term Ocoee is desirable, as the whole unit is more distinctive than its component parts, and as it differs greatly in its gross features from adjacent rock units. In this paper, the Ocoee is classed as a provincial series, probably belonging to the late pre-Cambrian. The Ocoee series is thus comparable to such other pre-Cambrian provincial series as the Keweenawan series, the Belt series, and the Grand Canyon series. Like them, it is a thick body of sedimentary rocks which can be subdivided locally into a number of formations.

The Ocoee series may be defined as comprising Keith's Snowbird formation, Hiwassee slate, Great Smoky conglomerate, Nantahala slate, and Sandsuck shale. As indicated on table 4, the writer believes that the sequence as interpreted by

Keith will require considerable rearrangement. Also, some of Keith's terms will need to be abandoned or more precisely defined, and some of the units will need to be subdivided.

The *Snowbird formation* at its type locality is divisible into a number of well-marked units which are probably equivalent to named units in the Great Smoky Mountains section, and it should be subdivided on this basis. The name might be useful, however, for the thinned equivalents of these formations toward the northeast.

The *Hiwassee slate* was named for the Hiwassee River, Polk County, Tennessee, where it forms a belt of outcrop many miles wide. In the Great Smoky Mountains the term should be abandoned, as it was here applied to diverse units in the Ocoee series, whose relations to beds in the type area are unknown.

The type area of the *Great Smoky conglomerate*, according to Wilmarth (1938, p. 865), is in the Great Smoky Mountains of the Knoxville quadrangle; probably it also includes outcrops of the formation in the Mount Guyot quadrangle to the east. It is here capable of precise delimitation, and should be restricted to the unit as defined in this area and its equivalents. Farther south, as in the Nantahala and Ellijay quadrangles, the term has come to be used as a general expression for rocks of Ocoee type. This usage is improper, and the term Ocoee series should be substituted.

The *Nantahala slate* has its type area in the Nantahala quadrangle. This area has not been studied by the present party of the U. S. Geological Survey, but the rocks exposed there appear to be the same as those to which the term is applied in the Great Smoky Mountains.

The *Sandsuck shale* was named for Sandsuck Branch, on Chilhowee Mountain, in the Knoxville quadrangle. Here the formation is directly overlain by the Chilhowee group; hence the term can be more precisely defined than the terms Wilhite slate and Hiwassee slate which Keith elsewhere used for equivalent beds.

In addition to these, the writer wishes to employ the term *Pigeon siltstone*, deriving the name from the same type area as the Pigeon slate of Keith's early work. According to Wilmarth (1938, p. 1658), this type area is the West Fork of the Little Pigeon River in the Knoxville quadrangle. Keith

(1895, p. 2) states that the Pigeon is extensively exposed in the drainage area of the Little Pigeon River, thus implying that it is also present along the Middle and East Forks of this stream in the Mount Guyot quadrangle. The Pigeon siltstone of present usage is widely exposed in the drainage areas of all three streams (fig. 8).

The formations of the Murphy marble belt (Tusquitee quartzite, Brasstown schist, Valleytown formation, Murphy marble, Andrews schist, and Nottely quartzite), which lie within the outcrop area of the Ocoee series (fig. 1), have been considered by some authors to be a part of the Ocoee series, but not by Safford. Their age and relations are uncertain, and they are not included in the present defir tion of the Ocoee series. In Safford's descriptions of outcrops in east Tennessee, he assigned to the Ocoee series in many places rocks which are now classed as parts of the Cochran and Unicoi formations. These are here excluded from the Ocoee and placed in the Chilhowee group.

The *Chilhowee group*, like the Ocoee series, was named by Safford (1856, pp. 152-153; 1869, pp. 198-203). It was not widely used by Keith in his folio work for he preferred, as in the case of the Ocoee series, to refer to the Chilhowee rocks in terms of their component formations. The need for a group name is indicated by the wide use of such informal terms as "basal quartzites" (Butts, 1933, p. 2), "Lower Cambrian quartzites and slates" (Geologic Map of United States, 1933), and "basal clastic group" (King and others, 1944, p. 27). The term Chilhowee group is appropriate for this purpose and has been so used by Butts (1940, pp. 26-27) and other authors.

According to Wilmarth (1938, p. 430) "the U. S. Geological Survey draws the base of the Chilhowee group at the base of the Cochran conglomerate and the top at the top of the Hesse sandstone." This usage corresponds with the usage of Butts and is followed in the present paper.

Unfortunately, Safford did not define exactly the base of the Chilhowee. In his description of Chilhowee Mountain (1869, p. 190) he states that strata of the Ocoee series are there exposed beneath strata of the Chilhowee group, which indicates that he placed part or all of what are now termed the Sandsuck shale and Cochran conglomerate in the Ocoee series. Elsewhere in east Tennessee, he generally excluded beds now classed as part of the Cochran conglomerate and Unicoi formation

from the Chilhowee, although he was not entirely consistent. A similar usage has been followed by the Tennessee Division of Geology in its geologic map of Tennessee, where beds here termed the Ocoee series and the Chilhowee group have been divided into an upper, or "Chilhowee" division, and a lower, or "Unicoi" division. The former included the Hesse quartzite, Murray shale, Nebo quartzite, and Nichols shale, and their correlatives. The latter included the Cochran conglomerate, the Unicoi formation, and all the Ocoee series below the Nantahala slate. According to the interpretations of the present writer, grouping of the Cochran and Unicoi with the Ocoee series is unnatural.

Lithologic titles have been given to many formations of the Chilhowee group—such as the Nebo, Hesse, Erwin, and Antietam quartzites, and the Nichols, Murray, Hampton, and Harpers shales. These lithologic titles are not useful in detailed work because the supposed lithologic units actually contain many other types of rocks. In the northeast Tennessee report (King and others, 1944, pp. 27-28) the lithologic titles were abandoned and the units were termed formations. In regional work the lithologic titles have some value as they express broad changes in sedimentation, and they are therefore employed in this paper. The term quartzite is used in this paper where it applies to a lithologic title of a formation; it corresponds to indurated quartzose sandstone and arkosic sandstone as used elsewhere in the paper.

Rock names.—The writer wishes, for purposes of this paper, to distinguish three types of medium-grained clastic deposits, which are termed *quartzose sandstone*, *arkosic sandstone and conglomerate*, and *graywacke sandstone and conglomerate*. The three types are readily distinguishable megascopically and in the field, and work that has been done so far by Mr. Hadley suggests that they may show equally well marked differences under the microscope. The first two types occur in the Chilhowee group and are more or less gradational, although the end members are distinct. The third type occurs in the Ocoee series and contrasts strongly with the other two. Published terminology of medium-grained rocks shows considerable variation from author to author,[11] and the terms as here used differ from some of the published definitions.

[11] Compare, for example, Allen (1936, pp. 18-47) and Krynine (1948, pp. 147-156).

The term *quartzite* is not used in this paper except as a part of already existing formational titles. It has been used in many previous reports on the southern Appalachians, but so loosely as to lack meaning, and without particular reference to the contents of quartz in the rock. The writer prefers the term *sandstone*, to which such modifying terms as quartzose, arkosic, indurated, and meta- can be added. If used, quartzite should be restricted to well-indurated quartzose sandstones such as those in the upper part of the Chilhowee group. Similar rocks have been called orthoquartzite by Krynine (1948, p. 149), but Allen (1936, pp. 38, 43) terms them silicinate quartz sandstones, and restricts the term quartzite to metamorphic rocks.

The terms *arkose*, *arkosic sandstone*, and *arkosic conglomerate* are used in the sense of Allen (1936, p. 44) for a sandstone containing 25 or more percent of feldspar, usually derived from the disintegration of acid igneous rocks. Those in the Chilhowee group contain more quartz than feldspar and very little of the other constituents of granite, such as mica and ferromagnesian minerals. They are well sorted and are probably subaqueous deposits. The term arkose has been restricted by Krynine (1948, p. 154), probably unjustifiably, to poorly sorted deposits, largely of continental origin, which occur in thick, lenticular sedimentary bodies.

The terms *graywacke*, *graywacke sandstone*, and *graywacke conglomerate* are used in the sense of Pettijohn (1943, pp. 941-943) for a primary sedimentary rock—a sandstone or conglomerate made up of grains of feldspar and quartz, with a large proportion of argillaceous matrix, and of characteristic gray or dark-gray color. Associated structural features such as intraformational conglomerates, graded bedding, and the great thickness of the deposit serve to set this rock type apart as a distinctive facies.

The term graywacke has been diversely defined, as indicated by Allen (1936, pp. 28-31). The Great Smoky conglomerate, which is here considered to be a graywacke in the sense of Pettijohn, has in the past been termed a graywacke on the basis of different definitions. Emmons and Laney (1926, pp. 15-16) refer to the primary sedimentary rocks of the Great Smoky as arkose and state that "intense regional metamorphism . . . produced from the arkose a graywacke." The

term is therefore used by them for a metamorphic rather than a primary sedimentary rock. Moneymaker (1938, pp. 293-294) criticises this use of the term graywacke and points out that such rocks are more properly termed gneisses. However, he fails to recognize that the less altered phases of the Great Smoky are of graywacke facies, because he accepts Twenhofel's little used definition of graywacke as "the basic equivalent of an arkose."

Stose and Stose (1946A; 1947, pp. 632-634; also paper of 1949) have used a rock classification which, so far as the writer is aware, differs from all others previously discussed. Two of their formations of the Ocoee series are termed the "Hurricane graywacke" and "Great Smoky quartzite." In the Great Smoky Mountains, the term "Hurricane graywacke" is used by them for rocks here termed the 'Pigeon siltstone." Both in the Great Smoky Mountains and at Hurricane village, North Carolina, these rocks are fine-grained, laminated, indurated siltstones, in part greenish and chloritic, in part with dark carbonaceous seams. In the Great Smoky Mountains, the term "Great Smoky quartzite" is applied by them to rocks here termed the Great Smoky conglomerate, which the writer considers to be of graywacke facies. The use of the term "quartzite" for these quartz-poor, highly feldspathic rocks, would seem to be difficult to justify.

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ANDEAN UPLIFT AND EROSION SURFACES NEAR UNCIA, BOLIVIA

EUGENE H. WALKER

ABSTRACT. Such knowledge of the physiographic development of the central Bolivian Andes as exists has been gained from a few rapid reconnaissances. Detailed studies in the region around Llallagua reveal a set of four erosion surfaces that show the stages of intermittent uplift of the Cordillera. Physiographic and paleontologic evidence lead to the conclusion that the area was relatively low-lying toward the end of the Pliocene and that most of the uplift to the present elevations occurred during the Pleistocene. There was slight mountain glaciation during the Pleistocene, but two terraces and stream bed alluvium suggest two stages of glacial climate. The region is now experiencing an increase in aridity.

INTRODUCTION

ALONG a section drawn east-west through central Bolivia (fig. 1) the Andes attain their greatest width, about 435 miles. This broad belt is composed of an eastern and a western cordillera separated by the Altiplano Basin. The rudiments of the geology of the Eastern Cordillera are known, for mining has been carried on at many widely separated points since the discovery of the Potosi silver deposit in 1545. Relatively little is known of the physiographic history. Moon (1939) gathered the scattered observations of many travellers and students but their data varies greatly in age and reliability. Gregory (1913) and Ahlfeld (1945) have discussed the origin of the spectacular gorge cut directly across the backbone of the Eastern Cordillera by the Rio La Paz. Bowman (1909, 1914) first noted the high level surface that truncates the Andean structures, and described the high shorelines that indicate the past higher levels of the Altiplano lakes, Poopo and Titicaca. Heald and Mather (1922), and Mather (1922) briefly mentioned a high erosion surface in the eastern part of the Eastern Cordillera. More recently Newell (1945, 1946) in the course of stratigraphic and structural work in the Lake Titicaca region, has clarified some of the events of the Tertiary.

With the intention of tracing the steps in the development of the Andean landforms the writer carried on field studies intermittently during the years 1942-45 in the region around Llallagua, where he was employed by the Patino tin mining interests. It is a pleasure to acknowledge here the aid given by

Marcelino Medrano of Cochabamba, Bolivia, who acted as muleteer, interpreter and guide on many a trip in canyon and high puna. In another sphere, the writer acknowledges his

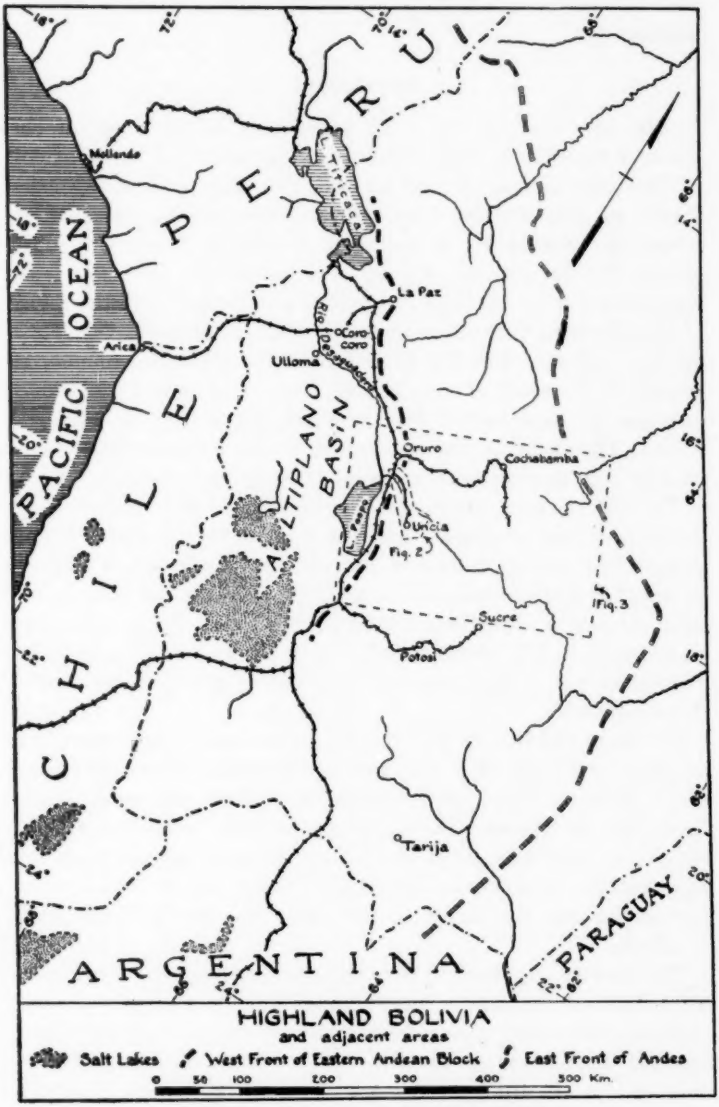

Fig. 1. Index map of Highland Bolivia.

indebtedness to Prof. Kirk Bryan of Harvard University for helpful criticisms and suggestions during the writing of this study. He also owes thanks to Prof. A. J. Eardley of the University of Michigan for his critical review of the manuscript.

GEOGRAPHY

The area studied lies a few miles east of the crest of the Eastern Cordillera, near Uncia (fig. 1), capital of the province of Bustillo. Llallagua and Catavi, the mine and mill settlements of the Patino Corporation, are nearby, and these towns are served by a railroad branching from the main line at Machacamarca (fig. 2). Machacamarca lies on a level plain which is an old lake bed, and a mile to the east the front of the Eastern Cordillera rises abruptly. The railroad climbs up the valley of the Rio Huanuni to the Paso del Bombo at 14,435 feet, where an extensive view is obtained of broad uplands of moderate relief, crowned by a few monadnock peaks. The total relief is somewhat more than 3000 feet, mainly due to deep valleys below the upland surface.

The elevation, coolness and semi-aridity of the area provide the steppe type of climate and the Andean bunch grass, *Stipa ichu*, is the strong dominant (pl. 1, fig. 2), though a carpet of shorter grasses usually is present between the clumps of ichu. At higher elevations a sparse growth of curious ground-hugging flowering plants gradually replaces the ichu, and in deep sheltered valleys some tall succulent grasses and a few shrubs appear.

Escobar (1943) shows the mean annual temperature to be about 9°C. (48°F.) and the precipitation about 400 mm. (15.7 inches). The precipitation is mainly as rain, from November to March. The mild winter then comes on and a couple of snowfalls of perhaps half an inch apiece may be expected, but hail is more frequent. Winter nights are frosty. Except during the rainy season the days are brilliant and cloudless.

The sparse vegetation permits rapid runoff so that torrents descend the minor watercourses during rainstorms, and all during the rainy season threads of water run in the braided channels that traverse the flat cobble-choked bottoms of the main valleys. In the succeeding dry season all minor streams

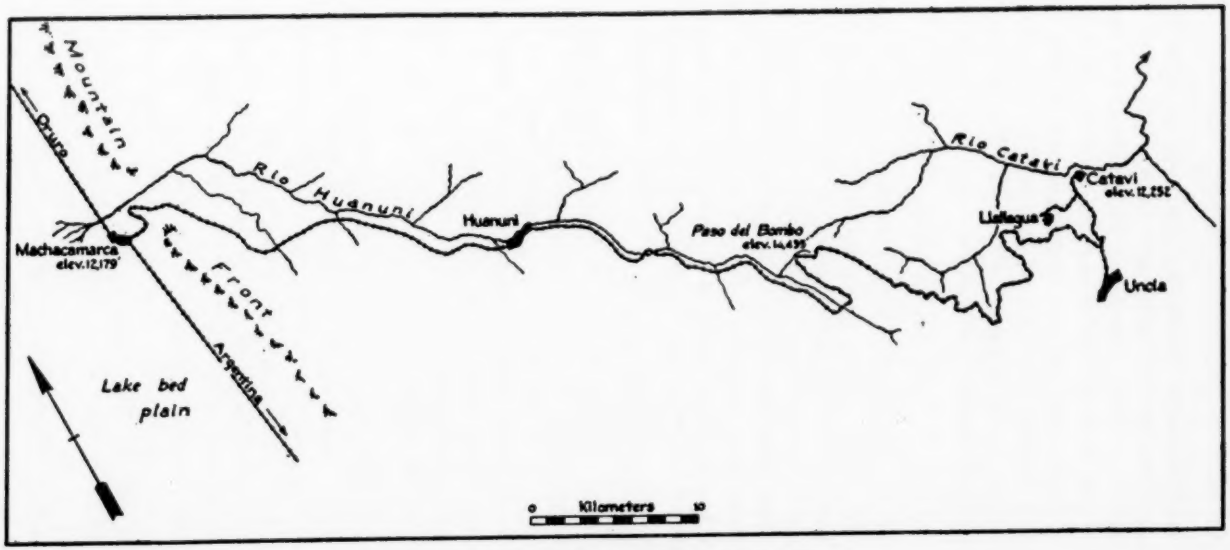

Fig. 2. Location map, Machacamarca-Uncía area.

are dry and the water gradually sinks out of sight beneath the surface of the alluvium in the main valleys.

The region is thinly populated by Aymara and Quechua Indians who have supported themselves since the most remote past by a simple pastoral and farming economy. The mining activity has introduced, more or less in the past 50 years, a town-dwelling population of about 30,000, mainly cholos (mestizos) of dominant Indian blood.

BEDROCK GEOLOGY

A section of about 6,000 feet of marine clastics and shales are exposed locally; they were first described by Koeberlin (1919). The strong Llallagua sandstone, about 200 feet thick, is a prominent ridge former. The rest of the sequence consists of greywacke, interbedded thin sandstones, and shales, all of intermediate to weak resistance to erosion. A few ill-preserved brachiopods found in a sandstone midway in the section are of Devonian age. Small patches of red continental sandstone and conglomerates lie with slight erosional unconformity upon the marine strata.

The Andean orogeny here created broad folds which strike northwest. Normally the folds are open, but stresses accumulated locally to cause overturned axial planes and thrust faults, both dipping steeply westward. A set of minor faults run northeast and cause short displacements of the northwesterly striking structures. A large normal fault runs north 30° west through Catavi and dips steeply west; the west side is dropped about 6,000 feet.

A volcanic neck, the Salvadora "stock," occurs along the axis of a large anticline. The cordierite-rhyolite of this body was greatly altered by the solutions that concentrated an enormous wealth of cassiterite locally.

Sheets of light gray tuff mantle broad areas. Though of similar composition to the rock of the volcanic neck, they lie on an erosion surface younger than the neck. The surface upon which they lie is undulating so that their thickness varies from about 150 feet to a feather edge.

The linear outcrops of resistant and non-resistant strata exposed along the fold axes have exerted the major physiographic control. The tuffs are resistant to erosion because of their light and porous nature which permits water to sink in rather than to run off. Thus the volcanics support mesas,

usually bordered by cliffs (pl. 2, fig. 2) which develop because of columnar jointing in the volcanics and undermining the seeps.

PUNA STAGE

In the vicinity of the Paso del Bombo, the divide between the drainage eastward to the Amazon and that westward to the Altiplano Basin, there are patches of a terrane characterized by broad rounded shoulders with intervening swales and meadow-like expanses. This topography is at elevations from 14,200 to 14,500 feet and is localized upon the rocks of moderate to weak strength, between or near outcrops of the strong Llallagua sandstone which supports long ridges that rise 150 to 350 feet higher (pl. 1, fig. 1). Unfaulted blocks of sandstone cause a few monadnocks to rise still higher; the prominent peak Espiritu Santo has an elevation of 15,364 feet.

This surface is considered the equivalent of the Puna surface that McLaughlin (1924) described in the region near Cerro de Pasco, Peru, where

> "In general, the surface truncated the complex structures of the Cordillera with indifference, except here and there, where the course of a particularly resistant stratum is marked by a hog's-back ridge, or where a mass of intrusive rock forms an isolated hill or prominent group of hills of Monadnock type."

"Puna" is the Quechuan word for the high and cool grassy uplands throughout the Andes. The presence of this surface in Peru has been verified by all later observers, most recently by Harrison (1943), and Newell (1946).

In the Llallagua region the remnants of the Puna surface decrease in area and practically vanish with increasing distance from the divide. The long hogback ridges on sandstone which stood above the surface persist still and give the even skyline of mid and far distance.

Heald and Mather (1922) recognized remnants of what is probably the Puna surface in the highland southeast of Cochabamba, and wrote that

> "During the late Tertiary (?) this area was a low-featured peneplain, which is now represented only by ridgetops and a few undissected remnants."

Still further south, in the sierras immediately west of Santa Cruz, Mather (1922) saw

> " . . . occasional upland surfaces with gentle slopes which

> bevel the upturned sediments and are ordinarily surmounted by slightly higher rounded knobs."

The high mature surface that Bowman (1909) noted on the border between Bolivia and Chile at the crest of the Western Cordillera inland from Iquique, may also be the Puna surface.

Fragmentary as the evidence is, it is apparent that throughout a vast area of the Bolivian and Peruvian Andes a distinct surface bevels structures and intrusives. The surface is probably broadly arched at present. The traces of it are lost in the angular scenery of the Eastern Cordillera before it has declined much in elevation, and it is possible that its remnants end against a line of great faults that Bowman (1909) and Mather (1922) consider to separate the mountainous mass from the Amazon lowland. McLaughlin (1924) states that in western Peru the surface is ". . . obliterated by erosion before it descends much lower than 12,000 feet . . . ." The surface that Bowman (1909) described in the Western Cordillera slopes gently toward the Pacific beneath a thickening cover of late Tertiary sediments and volcanic effusives.

Figure 3 presents the rectangular drainage pattern on the eastern side of the Eastern Cordillera. Lengths of subsequent streams have taken northwesterly courses parallel to the folded structure but long stretches of the major streams run northeast across the regional grain. These transverse links presumably are remnants of the drainage of the Puna stage. It is usual to consider such transverse drainage to have developed by superimposition from a cover such as the coastal plain sediments furnished on the east slope of the Appalachians. Since no traces of such covering sediments exist upon the Puna surface, the relations are most readily explained by assuming superimposition from a cover onto an old age surface which existed above the Puna surface, but which was here wholly destroyed in the making of the Puna surface. Such a surface may eventually be found beneath covering sediments in the subandean foothills to the east of the zone of uplift. The subsequent streams, in any case, testify to a long history of differential erosion and piracy since Puna time.

VALLE STAGE

Some 900 to 1,000 feet below the remnants of the Puna surface is a terrane developed broadly across the upturned sediments. Along the main drainage divide massive ridges exist

above this level but elsewhere only occasional monadnock ridges survive along parts of the outcrop of the strong Llallagua sandstone. The landscape at this level is one of valley floors, usually very wide, above which mountains rise 1,000 to 1,400 feet.

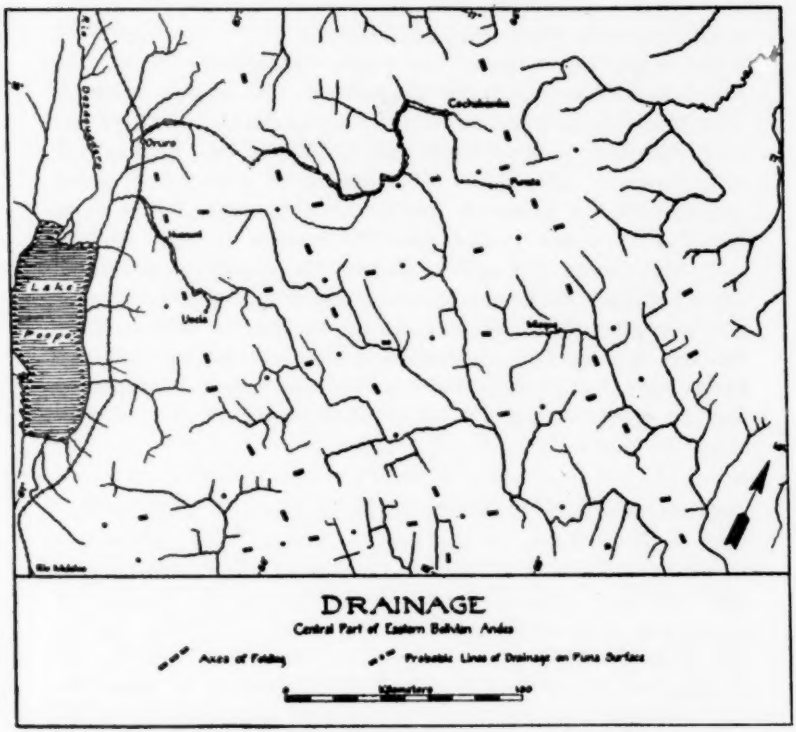

Fig. 3. Drainage of central part of Eastern Andes.

Volcanics, mainly firm tuffs, mantle much of this surface. In old valleys they may be 150 feet thick and they thin out upward on the old slopes. Usually the volcanics lie on bedrock that is weathered to a depth of several feet but in some places one may find stream gravels of quartzite marking buried drainage courses. The volcanics have diminished the local relief to produce the mildly rolling terrane typical of this main upland horizon (pl. 1, fig. 2).

These features record the following sequence of events. The slow course of erosion at the Puna level was interrupted by

uplift (and further west probably by faulting, as will be argued) which caused the streams to lower their courses approximately 1,000 feet before coming to grade. Long stillstand allowed reduction of most of the area to the new level. Weathering of bedrock and the existence of only resistant rock types, mainly quartzite, in stream channels testify to ample chemical weathering at this time.

Probably this interval of valley broadening should be correlated with the Junin stage that McLaughlin (1924) described, for in Peru, after the long stillstand of the Puna stage "An early, rather slight uplift, followed by a long period of quiescence, allowed the development of a series of broad valleys with flat gradients and gentle side slopes." The type locality, the Junin Valley, provided a name for this surface and stage. Since 800 miles separate the localities studied in Peru and Bolivia the correlation is uncertain and the present writer applies the name Valle to the surface in Bolivia. This Spanish word refers to broader and more mature drainage basins than the English word valley, and seems appropriate for the open terrane that resulted from the erosion of this stage.

CHACRA STAGE

About 500 feet below the Valle surface, or slightly less than halfway down to the present stream beds, there are traces of a surface. Along the valleys of main streams the vigor of later erosion has left of it only a few flat-topped spurs and occasional gravel-strewn benches. Larger tracts, still little dissected, persist along the courses of those minor streams and headwaters that had the fortune to lie upon the less resistant bedrocks. Such an area is illustrated in plate 2, fig. 1. Another prominent trace of this surface (pl. 2, fig. 2) owes its preservation to a piracy which greatly weakened the stream that crosses it; the stream is now intermittent and so incompetent that even though it crosses soft shales a hanging junction has developed where it joins the main stream.

This surface is important chiefly as evidence of a pause in the major downcutting of post-Valle time. The volcanics that blanket the Valle surface were perhaps the surface manifestation of deep seated disturbances accompanying a regional uplift that brought about renewed downcutting. In some cases the slopes beneath volcanic cover incline gently toward the pres-

ent valleys, indicating that the main streams were able to hold to their courses, though the pattern of the minor streams was effaced. Downcutting continued for about 500 feet, at which point a pause allowed valleys to be broadened upon softer bedrock.

This surface seems likely to correlate with the benches McLaughlin (1924) described in Peru midway between the uplands and the valley floors and is given the same name. "Chacra" signifies a small plot of tilled ground; here in Bolivia as well as in Peru much of the cropland of the Indians is at this level, below the bleak uplands and above the generally stony valley floors.

PIEDMONT STAGE

A very obvious surface of planation lies 400 to 500 feet below the Chacra remnants and 150 to 200 feet above the stream beds. Along those portions of the valleys floored with shales and thin-bedded sandstones are expanses as much as several miles wide, the "pampas" of the region. These old valley floors constrict to canyons at the outcrops of the Llallagua sandstone. No counterpart of this surface has been described elsewhere and it will be referred to as the Piedmont surface since it forms so prominent a footslope below most of the local relief.

It is characteristic of this surface that bevelled bedrock inclines toward the valley centers (pl. 3, fig. 1). Where bedrock is mantled with alluvium (pl. 3, fig. 2) the sloping bedrock can be seen in the walls of the quebradas or gulches that trench below the alluvial cover. We have here a rock pediment rather than a surface of lateral planation. The alluvium reaches a thickness of 100 feet in some places but always thins to a frayed edge toward the hill and mountain slopes.

At its base the alluvium is coarse and cobbly, but not badly sorted; low grade placers of cassiterite have encouraged some prospecting. Upward from the base the grain size at first decreases slightly; then a transition sets in and particle size increases till the alluvium becomes even bouldery. Some of the stones are ill-rounded, many of them bear the percussion marks showing handling by torrential streams. This coarse material grades unevenly upward through finer grained zones and at the top of the section there are lenses of sand and silt.

At one locality there is in the upper part of the sequence a thin bed of peat. It is reported that a number of years ago the remains of a mastodon were found in the higher part of the alluvium.

The significant downcutting from the Chacra surface indicates resumption of the spasmodic Andean uplift, and the pediment surface strongly suggests drier conditions than previously. The lower alluvium can probably be considered a normal accumulation on a pediment graded to an incompetent stream, but some explanation must be found for the change midway in the alluvial section.

The coarsening of the alluvium apparently records accelerated erosion of slopes and delivery of excessive loads to lowland streams. The writer believes that this was due to the onset of glaciation in the Andean region. Snowline was high here, for only above 13,500 feet are there striated outcrops and there are no obvious moraines. Waste was not moved down to the valley floors by ice. However the colder climate undoubtedly increased the available supply of waste because of frost breaking of rocks and decreased vegetation cover, and solifluction would hasten material downslope. Valley trains of alluvium were spread.

During the waning stages of glaciation finer sizes of sediments were deposited. The mastodon remains and the patchy peat deposits indicate a cool and damp climate toward the end of this period, with broad marshy valley flats traversed by braided or meandering streams.

LATER PLEISTOCENE STAGE

Below the Piedmont surface some 200 feet or less there are flat valley floors strewn with coarse alluvium (pl. 3, fig. 2). West of the divide and downstream from the Huanuni mine the valley of the Rio Huanuni is at places more than a mile wide and the gravels are so thick that a large floating dredge is employed to work them for their cassiterite content. This particular sheet of alluvium was clearly graded to the level of a lake which occupied the Altiplano Basin to the west and which left prominent shoreline features about 115 feet above the basin floor. This was Lake Minchin; lake bed sediments and the delta deposits lain by the Rio Huanuni have been exposed near Machacamarca by later stream cutting.

REMNANTS OF THE PUNA SURFACE
Foreground elevation about 14,400 feet. Puna surface at (a); monadnock on Puna surface at (b).

VALLE SURFACE MANTLED WITH VOLCANICS
Foreground elevation about 13,500 feet. Puna ridgetop at (a); upland on volcanic mantle at (b); bedrock hills of Valle surface at (c).

HEAD OF HUANUNI VALLEY

Foreground elevation about 14,300 feet. Level skyline at (a) is Puna surface; at (b) a portion of the Valle surface preserved beneath volcanic cap; the Chacra surface, little dissected is at (c).

CHACRA VALLEY

Volcanics overlying Valle surface at (a). The light colored zone marks the base of the volcanics. The Chacra surface at (b) has here an elevation of about 12,700 feet.

FIGURE 1. MIDDLE COURSE OF HUANUNI VALLEY
Elevation of immediate foreground is about 13,000 feet. At (a) is a large remant of the Chacra surface; at (b) the Piedmont benches cut across folded shales and thin sandstones.

FIGURE 2. VALLEY OF RIO CATAVI
At (a), elevation 12,400 feet, the surface of the alluvial fill on the Piedmont surface; at (b), the braided channel of the Rio Catavi. Immediately above (c) is a small patch of the Chacra surface, downstream from a gorge cut across the Llallagua sandstone.

The trenching of streams below the Piedmont surface began after the first glaciation, and locally the streams lowered their courses as much as 100 feet into the bedrock beneath the alluvium. Renewed alluviation seems to have been due to a second period of glacial climate. The deep fill in the lower part of the Huanuni valley evidently is due to the fact that the gradual rise of Lake Minchin lifted the base level of the Rio Huanuni at least 115 feet and caused aggradation far upstream. East of the divide streams are locally graded to strong beds outcropping in their channels and ultimately to the Atlantic, so local aggradation was due to overloading during glacial climate.

RECENT EROSION

Due to the disappearance of Lake Minchin, the Rio Huanuni and other streams draining westward to the Altiplano Basin have begun to trench their valley fill. The nickpoint in the Huanuni valley has advanced only about three miles upstream. In general, erosion in main stream beds is taking place very sluggishly due to coarseness of the load to be removed, and small supplies of water. East of the divide, however, the great drainage systems slowly concentrate many trickles of water into single channels, with the result that erosion increases rapidly downstream.

At the present, hill slopes are being gullied, and small arroyos are being cut in the alluvial floors of many tributary streams. Here most of the steep slopes are very thinly covered with bunch grass, others are almost totally barren. Without doubt this erosion is partly due to the land use tactics of the Indians. The search for fuel is intense; hardly a bush survives after its stem attains the thickness of a lead pencil. The bunch grass may be hauled up roots and all for fuel or thatching. The more palatable grasses are cropped closely by sheep and llamas. The marvellous and laboriously built andenes or rock walled terraces built in ancient time still persist on the hill slopes, but the narrow strips of soil they provide are now neglected in favor of larger fields of considerable slope. The accelerated erosion is therefore partly induced by land use.

It is proper, however, to point out the evidence of increasing aridity. The level of Lake Titicaca in the northern part of

the Altiplano has been falling slowly for decades, so that the approaches to steamship wharves have had to be dredged repeatedly. The volume and depth of the Rio Desaguadero, the outlet of Lake Titicaca, have notably decreased with the result that Lake Poopo receives less water and has shrunk greatly. Slope erosion in Bolivia, as in the southwestern United States, is due probably to a combination of climatic change and severe use.

SUMMARY OF HISTORY AND DATING OF EVENTS

In the area under discussion paleontologic evidence for dating the surfaces and events is absent so it is necessary to establish correlation with areas where such evidence, scanty as it may be, does exist.

The cutting of the Puna surface is the first event for which a date is required. The surface truncates the folds and intrusives of the Andean region so the date of the orogeny sets a maximum age limit to the surface. Unfortunately the date of the orogeny is still disputed. Berry (1919) assigned the orogeny to the late Pliocene because he dated as Pliocene the plant leaves that are found in the folded sediments at Coro-Coro in the northern Altiplano of Bolivia. At Potosi, sediments with similar leaves are little deformed, but are cut by a volcanic neck.

Near Ulloma, in the broad valley of the Rio Desaguadero south of Lake Titicaca (fig. 1) the slightly consolidated "Puna" beds lie essentially horizontally upon a surface that bevels the older folded sediments. The surface is probably the Puna and in any case it can hardly be older. The Puna beds contain a rich mammalian fauna of *Hippidion*, *Mastodon*, *Scelidotherium*, *Mylodon*, and *Megatherium*, which Philippi (1893) dates as Upper Pliocene. This occurrence suggests that the Puna surface was fully developed at or before the end of the Pliocene.

The evidence from these two localities is conflicting, or at best allows only a fraction of Pliocene time for the folding, intrusions, uplift and long erosion. The recent tendency has been to ignore the date assigned to the fossil leaves and to make the orogeny earlier than Pliocene. Turneaure and Welker (1947) believe that the intrusives date from some part of the interval between the Eocene and the Pliocene;

Steinmann (1929) has shown that much if not all the folding in Peru is early Tertiary, and Bruggen (1934) finds a similar date in Chile. Ahlfeld (1941) writes

> "Groeber maintains that the principal Andean folding in northern Argentina took place in the interval between the Oligocene and the Miocene. As long as the exact determination of the age of the folding in Bolivia is not possible, we are going to accept that this took place at the same time as in northern Argentina."

In his recent paper Newell (1946) refers the latest Andean folding to the Miocene.

The evidence is therefore fairly strong that the erosion of the Puna stage took place during a large part of Pliocene time and the surface was completed and locally mantled with the Puna beds before the end of the Pliocene.

The undisturbed Puna beds raise a problem as to their origin and relations to the later erosion surfaces. Patches of these sediments occur throughout the Altiplano Basin. At Ulloma, Ogilvie (1922) reported " . . . reddish and yellowish sands with irregular lenses of gravel and occasional marl and clay bands . . . ," while nearby at Mauri Ahlfeld (1941) mentioned rose colored marls and sands and conglomerates. In the valley of La Paz the writer has seen loose red and white sands interbedded with conglomerates containing pebbles from the Tertiary granites not far to the east.

Similar beds lie in local basins within the Eastern Cordillera, at Cochabamba and at Tarija, according to Oppenheim (1943). In the southernmost part of Peru, just north of Lake Titicaca, Gregory (1914) and Eaton (1914) found and described basin sediments of the same type. Their locality is near Ayusbamba in the Upper Apurimac Basin, where loosely consolidated sands, clays and marls lie with great angular unconformity on folded bedrock. The beds are remarkable for their fauna of *Camelidae*, *Equidae*, *Cervidae*, *Elephantidae*, and *Mylontidae* of late Pliocene or early Pleistocene age.

These occurrences have in common their considerable altitude, ranging from 8,500 feet at Cochabamba to 12,300 feet at Ayusbamba, the great unconformity separating them from the older rocks, and their lithology. They are the clastics deposited in stream channels, on flood plains and deltas, and

the marls and clays of lakes and swamps. Red beds are common. Drainage was to local basins rather than through-going. The climate was warm and the land low-lying if we take the red beds to signify tropical or sub-tropical weathering of the source areas, and clearly the herbivores required abundant vegetation.

The change from the through-going drainage upon the Puna surface to the basin drainage indicated by the Puna beds is most reasonably explained by assuming that block faulting took place. Moon (1939) first suggested faulting as an explanation for the basins, although McLaughlin (1924) had earlier considered that " . . . some warping and possibly block faulting . . . " ended the Puna stage in Peru. Newell (1946) agrees that the Altiplano Basin of Bolivia is probably a broad crustal segment downdropped with respect to the Eastern Cordillera. The relatively straight west front of this Cordillera is the much eroded fault line scarp.

The new relief provided by this faulting set erosion to work upon a weathered terrane. Part of the detritus accumulated in the Altiplano Basin and the smaller intermontane basins to form the Puna beds, part was removed eastward toward the Amazon Basin. The east-running streams gradually opened out the Valle surface, to be dated as Plio-Pleistocene because of contemporaneity with the Puna beds.

As previously mentioned, lithology and fauna of Puna beds indicate low-lying land. The subsequent uplift, which amounts to about ten or twelve thousand feet in some places, must have taken place in the Pleistocene. A similar conclusion as to the recency of the Andean uplift was obtained by Harrison (1943) from his work in Peru. If one million years are allotted to the Pleistocene (Zeuner, 1945), the rate of uplift if steady would have been about 0.01 feet per year. The post-Valle erosion surfaces show that uplift was not continuous, so the rate must have exceeded this figure considerably at times.

The volcanics emitted in the Llallagua region at the close of the Valle stage apparently have their counterparts throughout the Andean region, for vast areas around and east of Potosi are thickly blanketed. To the north volcanics are still widespread, but much thinner. At Mauri the Puna beds are overlain by tuffs, and dacitic ash is mingled with the upper beds at Ayusbamba. It is probable that the great volcanic

piles of the Western Cordillera began to form at this time. The region-wide vulcanism, as well as the climatic change due to uplift, was no doubt a factor contributing to the extinction of the herbivores of the Puna beds.

The Chacra surface is early Pleistocene and significant only as evidence of pause during uplift. The rock-cut floor of the Piedmont surface is a pediment and gives the first evidence of semi-arid climate. This climate may have been due merely to elevation and position far inland; it may also mean that by this time the Western Cordillera had grown high enough to further modify the inland climate.

The nature of the alluvial fill upon the Piedmont surface furnishes evidence of the first of the two glacial stages recorded in the Andes. This stage should be recorded by high shorelines in the Altiplano Basin, but in the southern part of the Basin no such shoreline except that of Lake Minchin is evident. Up to 100 meters or 330 feet above Lake Titicaca are the shorelines of Lake Ballivian described by Bowman (1914) and others (see Moon 1939). Newell (1946) believes that the first lake to occupy the Titicaca basin was pre-glacial, but some of the beaches above the present lake may eventually be shown to illustrate the first and second glacial stages.

In the Llallagua area an interglacial is clearly evident in the interval of erosion that separates the two stages of alluviation, and the second stage of alluviation has, in the case of the streams draining to the Altiplano, been directly correlated with the Lake Minchin beach.

The climate is at present suitable for the formation of pediments and this is the form now developing west of the divide in response to the more or less stationary base level furnished by the Altiplano Basin. East of the divide the slow pace of stream-bed erosion is due to be quickened fairly soon. The Rio Catavi, which may be taken as typical of east-running streams, has an overall gradient of 131 feet per mile in the first 35 miles of its course downstream from Catavi. Canyons will be cut before grade is reached. The divide between east- and west-running drainage is destined to shift westward until ultimately the Altiplano Basin will be drained eastward to the Amazon. This stage of drainage development has already been reached in the northern part of the Altiplano Basin;

the gorge in which La Paz lies is a trench excavated in the soft fill of the Basin by a headwater of the Amazon.

CONCLUSION

The principal aim of the writer has been to establish a satisfactory outline of the events of the late Tertiary in the Eastern Cordillera of Bolivia. This has involved reference to other localities about which a meager amount is now known. A framework of reference has been provided, however, for the scattered observations that will slowly accumulate, and perhaps for further systematic studies in small areas. The high Andes offer a practically virgin field for geomorphic study; the stages of glaciation and the glacial lakes are perhaps the most important problems inviting study.

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THE JOURNAL CHANGES EDITORS

With publication of the July number this year, the name of Richard S. Lull, Editor for many years, disappeared from the cover of this JOURNAL. Logically that issue should have carried an explanation of this event, about which most of our readers had no advance notice. However, Professor Lull's successor was just returning to New Haven and adjusting his schedule after nearly a year of field work in the West. Moreover, in midsummer large numbers of the JOURNAL family are away from their reading tables. September, beginning the season of return to indoor tasks, is an appropriate month for this announcement.

Professor Lull became Editor-in-chief of the JOURNAL at the start of the year 1933, just three and a half years before retirement from his professorship at Yale. Thus he kept the editorial post for sixteen and a half years. Up to 1938 he exercised full duties as Director of the Yale Peabody Museum; and he still occupies his office in the museum building, carrying on his research in vertebrate paleontology. He relinquishes the editorship, but retains his keen interest in science and in the JOURNAL.

In looking through a full set of the AMERICAN JOURNAL OF SCIENCE, which has run without interruption from 1818 to the present, we discover only three predecessors of Professor Lull whose names have appeared in first place on the front cover. These men, with dates of their incumbency, are as follows: Benjamin Silliman, Sr. (founder of the JOURNAL), 1818-1870; James Dwight Dana, 1871-1894; and Edward S. Dana, 1895-1932. In fact, however, Alan M. Bateman and Ernest Howe performed full duties as Editor, the former in the period 1925-26, the latter from 1927 through 1932, although both these men chose, as a courtesy to Professor E. S. Dana, to print his name ahead of their own. Furthermore from 1838 through 1864, Benjamin Silliman, Jr., shared the editorial duties, and his name followed his father's on the cover. In the

period 1846-1864 the name of J. D. Dana was added to form a triumvirate that endured until the younger Silliman withdrew. The elder Dana continued to assist Benjamin Silliman, Sr., through 1870; and during much of the period 1871-1894, the name of E. S. Dana was carried with that of his father. Actually, therefore, six men had served as editor of the JOURNAL during the 115 years ending in December, 1932.

Professor Lull assumed the editorship at a difficult time, in the worst part of the economic depression. His administration brought the JOURNAL through that period, and also through the hard years of the war when subscription lists suffered and production of scientific papers was at low ebb. He comes of a family with a long naval tradition, and in his jovial parlance he has now "turned over the ship." In the same spirit we salute him as a gallant skipper who has brought the ship through fair weather and foul, and has turned it over in seaworthy condition to a new command.

John Rodgers, who began as Assistant Editor in the fall of 1948, continues in that capacity, thus supplying an effective link between the two administrations. To readers and contributors, the new editors promise their best efforts to maintain the high standard of service set by Professor Lull and his predecessors.

CHESTER R. LONGWELL.

REVIEWS

The Structure of Matter; by FRANCIS OWEN RICE and EDWARD TELLER. Pp. xiii, 361. New York, 1949 (John Wiley and Sons, Inc., $5.00). In this work, the authors attempt "to acquaint the reader with the scope of the phenomena that can be explained with the help of quantum mechanics." Their aim has been to accomplish this with the minimum use of mathematics, and even the Schroedinger equation was omitted on this account. The result is a book which should be of real value to those who wish to gain a qualitative feeling for the quantum mechanical approach. For many applications, this may be all that is necessary, since the problems are so complex that the difficulties of a rigorous, mathematical treatment are insuperable.

The book is outstanding for the way the authors have succeeded in presenting concrete models for the often tenuous abstractions of the formal theory. They have accomplished this by a liberal use of diagrams the significance of which is carefully explained in the text.

The range of material covered is wide, ranging from the structure of the hydrogen atom to the sources of energy in the stars and the genesis of the chemical elements. Among the thirteen chapters are treatments of the periodic system, the chemical bond, intermolecular forces, the interaction of matter with electric and magnetic fields, molecular and atomic spectra, nuclear chemistry, and the solid state. As might be expected in an attempt to cover so wide a range of subjects, some of the topics are not covered in so refined a manner as might be desired by a specialist in the particular field. In many cases, however, quite sophisticated concepts are clearly presented. A notable example is the treatment of the modern theory of metals.

It is unfortunate that a book such as this, which is intended as an introduction to a large number of specialized fields, should include almost no references to works to which the reader can turn for more information about some specific phase of the subject. A selected list of general references for each chapter would increase the value of the book considerably. The book is also somewhat more limited in its scope than its title would indicate in that it treats only the properties of the atoms and molecules of which matter is composed. The way in which molecules cooperate to produce macroscopic effects, as discussed in the kinetic theory of matter and statistical mechanics, comes in only incidentally. This limitation excludes any coherent explanation of the properties of liquids and gases.

The book will be of interest to almost all scientists, and will be of particular value to those working in fields in which the rigorous application of quantum mechanics is impractical, but in which the quantum mechanical method of thought may furnish a useful guide in interpreting the observed phenomena. HENRY C. THACHER, JR.

Sedimentary Rocks; by F. J. PETTIJOHN. Pp. xviii, 526; 40 pls.. 131 figs. New York, 1949 (Harper & Brothers, $7.50). Professor Pettijohn's contributions to the study of sedimentary rocks are many and important. One thinks at once of his studies of Precambrian sediments in the Canadian shield and of the widely used *Manual of Sedimentary Petrography* prepared jointly with W. C. Krumbein. His new book on sedimentary rocks is therefore a welcome addition to the literature of the field.

The book contains a great deal of valuable information, grouped around three major themes: properties of sedimentary rocks (chapters 2-5), kinds of sedimentary rocks (Chapters 6-11), and processes that form sedimentary rocks (Chapters 12-15). The line drawings are many and clear, and the constant use of triangular and other quantitative diagrams continues the excellent trend established in the *Manual of Sedimentary Petrography*. The 40 collotype plates, showing specimens, outcrops, and especially thin-sections, are among the finest illustrations this reviewer has ever seen in a textbook. The book itself is a fine example of good book-making.

Unfortunately, the material presented in the book shows signs of hasty compilation instead of the thorough working and reworking, rearrangement and checking, that the reader has a right to expect of the author. Some of the results are merely vexing, such as inadequate proof-reading, as in references and technical terms, frequent lapses in grammar, and poor organization. More serious is the failure to make various parts of the book consistent and to digest the material presented so that a clear summary of existing knowledge (and ignorance) emerges. On several subjects, for example oolites in Chapter 2 and abrasion and sorting in Chapter 13, the student is overwhelmed with pages of (frequently contradictory) results from the literature, but the subject is never summarized or generalized by the author. Not that the author needed to generalize arbitrarily among the contradictory data; even a summary of the contradictions and their implications would have been very helpful. As it is, unexplained contradictions abound (there are four on page 269 alone), and though doubtless all of these can be explained without difficulty, it is unfair to ask the elementary student to figure out each one without help from the author.

The fine aspects of the book, however, such as the great number of references scattered as footnotes through the text, will make it a good source for more advanced students. The last two chapters (on deposition and lithification) are especially good and are freer from errors (though even here fig. 116 contradicts the adjacent

text and fig. 115 its own caption). Chapter 14 (Deposition) is a competent statement of the current tectonic interpretation of sedimentary sequences, and here the author has not been afraid to generalize (though as a result one reads that carbonate rocks are virtually unknown in the "flysch" facies whereas they form a considerable part of the type Flysch, and that the Alpine Molasse is red whereas it is gray and green). There is so much good material here, and Professor Pettijohn is so well qualified to present it, that one can only hope that he will take the necessary time to revise the book with care, checking throughout for inaccuracies and contradictions, and digesting and summarizing the rich but chaotic literature, so that students will find the book a safe and adequate guide. JOHN RODGERS

Map of the Americas, 1:5,000.000 (5 sheets, each 46 x 35 inches), $20.00. *Map of the World*, Miller cylindrical projection, 1:30,000,000 (57 x 35 inches), $2.50. American Geographical Society, New York.—The American Geographical Society has now completed its 1:5,000,000 map of the Americas, of which the three Latin American sheets were published in 1942. The map, plotted on a conformal double conic projection especially computed to procure minimum distortion throughout the Americas, is a fine example of the Society's high cartographic standards. Layer tints on land and sea emphasize the physical relief, and the principal streams, towns, roads, railroads, and airfields, and the country and state or province boundaries are shown. All available information was canvassed, and in places, as in the Canadian Arctic, the map shows data not hitherto shown on any map of like scale. Indices to all names given on the map are available.

The Society has also released recently a map of the world (except for Antarctica), showing land elevation (by six layer tints), the principal rivers and towns, and international boundaries (mainly as of 1947). This map also is on a new projection, which avoids the extreme expansion in high latitudes inherent in the Mercator projection, but at the expense of very considerable distortion, A diagram on the reverse facilitates determination of great circle distances and routes. JOHN RODGERS

Klockmann's Lehrbuch der Mineralogie; by PAUL RAMDOHR. Thirteenth edition, Pp. xii, 674. Stuttgart, 1948 (Ferdinand Enke Verlag, DM 50.00).—This excellent textbook of mineralogy brings to date a long series of editions that have appeared under well known names. The book contains two major divisions, (I) general and (II) descriptive mineralogy. General mineralogy is subdivided into (1) physical mineralogy, including crystal form,

crystal fine-structure, and physical properties; (2) chemical mineralogy and crystal chemistry; (3) formation of minerals in nature, including geologic setting, mineral deposits, paragenesis, and an interesting list of 81 famous mineral localities with the important and characteristic minerals of each; (4) mineral uses. The descriptive division is conventionally divided into sections based upon a crystallo-chemical classification of minerals, largely following Strunz's *Mineralogische Tabellen* (1941).

In briefly reviewing so inclusive a book, only a few points of special interest can be selected, other equally important ones being necessarily omitted. Ramdohr's crystallographic nomenclature could be made more useful by the inclusion of the Hermann-Mauguin class symbols and space-group symbols instead of (or in addition to) the Schoenflies symbols which adequately describe only the 32 classes (serial numbers for space groups isomorphous with each class can hardly be considered "adequate"). In general, the approach to crystallography and crystal structure is modern and satisfactory. It is somewhat heavily weighted in favor of morphology.

It is not satisfactory to find more than one system of nomenclature for the principal refractive indices. The symbols used in the general descriptions of methods and principles are the widely-known Greek letters α, β, γ, ϵ, ω. In some of the mineral descriptions we find the same symbols; but in other descriptions we note n_o, n_e; and in still others we find n_ω, n_ϵ, n_α, n_β, n_γ. There may be some justification for n_o and n_e—*n* clearly implying *refractive index*, and the subscripts indicating the name of the ray or vibration direction involved. But the use of the Greek letters as subscripts after defining them in accordance with common German usage as the refractive indices for certain rays, seems most undesirable. If *n* is to be used, its subscripts should refer to the vibration axes (either x, y. z. or **a**, **b**, **c**,) should not be the symbols that independently denote refractive indices. Least desirable of all is the apparently indiscriminate mixture of several systems of symbols.

HORACE WINCHELL

Minerals and How to Study Them; by the late EDWARD S. DANA, revised by Cornelius S. Hurlburt, Jr. 3rd Ed. Pp. x, 323; 387 figs., colored frontispiece. New York, 1949 (John Wiley & Sons, $3.90).—This book, intended specifically for beginners in mineralogy who lack the scientific background to attempt the more comprehensive texts, will be welcomed as a timely revision of a book already popular in its field. It is the least advanced in the Dana series of mineralogies, which includes also the *Manual*, the *Textbook*, and the *System*.

Doctor Hurlburt's revision has consisted chiefly of three things: first, rephrasing of the late Mr. Dana's words in a style better suited to the present day, while not losing a bit of their cogency and clarity; second, introduction of new material which has come as a result of over half a century of scientific progress; third, complete rewriting of the section on descriptive mineralogy, both to change the classification to that based on groups of chemical compounds, now nearly universal, and to make the individual descriptions of species more coherent and adaptable to reference. Discussions of the basic mineralogical concepts, such as the definition of a mineral, have been brought into accord with current ideas. An interesting section on crystal growing has been introduced, enabling the student not only to see for himself how crystals may be formed, but also to possess crystals well enough formed for study, without having to buy expensive specimens from a dealer.

In the opinion of this reviewer the book is open to criticism on only two points of any significance. Firstly, it is doubtful if the brief explanation of polymorphism given would make quite clear to the beginner that the polymorphs differ in atomic structure, though the atoms involved are exactly the same in both kind and number. Secondly, a few of the diagrams in the section on crystallography contain errors which the crystallographer would recognize as such, but which might easily lead to misunderstanding on the part of the impressionable young beginner. An example is figure 45, showing the tetragronal axial cross and the first order tetragonal prism: the a_2 axis fails to intersect the edges of the prism. Such errors may not seem serious, but it might be remembered that this book is intended for beginners and should impress upon them the need for accuracy and precision in advanced study of the subject.

Doctor Hurlburt has produced a commendable revision. The illustrations, with the exceptions noted above, are good, and a very definite improvement over the previous edition is the use of actual photographs to illustrate some common mineral habits. There are few typographical errors, and the general make-up of the book allows easy and enjoyable reading. It is a worthwhile addition to the library of any beginning mineralogist. WALDEN P. PRATT

Animals Without Backbones: An Introduction to the Invertebrates; by RALPH BUCHSBAUM. Revised edition. Pp. xii, 405; 160 pls., and numerous figs. Chicago, 1948 (Chicago University Press, $6.50). Intended as an introduction to invertebrate zoology for college students this lively textbook has found wide use at several scholastic levels and has gained a popular following as well. While definitely not a popularization of the subject, the interesting nontechnical style and excellent illustrations put the subject matter

within the grasp of the interested layman. As a text it is unusually adaptable because the author has organized the material in such a way that either a general or a detailed survey of the subject can be made without loss of continuity or omission of basic principles.

The text of the revision remains much as it was in the first edition except for the changes necessary to bring it up-to-date and for the addition of a short chapter at the end of the book. This new chapter, entitled *Further Knowledge*, introduces the student to scientific literature, explaining the fields of specialization within the biological sciences and giving their principal media of communication. A selected bibliography of about 70 items bearing on the invertebrates is included and three short scientific articles, reprinted in their original form, serve as examples.

One minor criticism of the text is its lack of any reference list showing, in its entirety, the classification of invertebrates used in the book. The omission is especially noticeable in light of the fact that an entire chapter is devoted to the subject of classification.

The new edition is even more copiously illustrated than its predecessor with thirty-two new pages of excellent gravure illustrations appearing in the photographic sections. By bringing together such an exceptional collection of photographs Buchsbaum has indeed accomplished his stated aim of giving the student a vicarious field experience.

The revised edition of *Animals Without Backbones* will be welcomed by teachers of elementary zoology and paleontology. It is an outstanding general science text and sets a standard that other college texts at this level may well imitate. KARL M. WAAGÉ

Recent Marine Shell-Bearing Mollusca of the South Sea Islands (*Part* 1); by KOTORA HATAI. Bulletin 7., Tropical Industry Institute, Palau, South Sea Islands. Occasional Paper No. 24, Institute of Geology and Paleontology, Tohoku Imperial University, Sendai, Japan, 1941. Published in 1941, this is an admittedly incomplete work, planned as the first in a series on the recent shell-bearing mollusks of the South Sea Islands. The author has covered the larger and more spectacular gastropods and pelecypods quite thoroughly, and subsequent volumes undoubtedly were planned for the smaller and less well-known mollusks. The war, of course, halted all activities of this nature, and it is now problematical whether or not the original project will ever be carried out.

The report is in two volumes: part A consisting of 159 pages of text, and part B of 79 plates. The author gives a brief quotation from the original description for each species, and discusses its known geographic range. Throughout the text the generic names that are familiar to all shell collectors are used. Thus all of the

cowries are under the genus *Cypraea,* notwithstanding that the genus has been split into several genera by modern malacologists. However, in the fore part of the book the modern classification of Dautzenberg, Leloup, and others is given. This seems an admirable arrangement, as the non-specialist can find his shells easily by the names they have carried for scores of years, and a quick reference to the modern list will give him the up-to-date name.

The illustrations are generally excellent. Reproduced in collotype, each shell is shown in two or more views, and all but the very large varieties are at natural size. The photography and reproduction are both excellent, but the choice of specimens for illustration was not in every case a happy one. A few characteristically marked species such as *Conus marmoreus* and *Cypraea argus* are illustrated by worn shells that fail to show the mollusks' true beauty. Also, some of the common and well-known shells such as *Cypraea mappa* and *Conus imperialis,* present in nearly every lot of shells from the South Seas, are not illustrated, altho they are mentioned in the text. The lack of an index is disappointing.

Nearly every small city museum and preparatory school, and many high schools and libraries, have boxes of sea shells that have been "donated" at one time or another. Our returning service men and women have probably brought back tons of shells from the South Sea area, and in the years ahead it is likely that more and more "donations" to local institutions will be made. The present work should be extremely useful to the curators of such institutions, as it would be a simple task to get the correct name and approximate locality of almost any of the commoner shells from this area. P. A. MORRIS

Tellus, a quarterly journal of geophysics.—A new journal has been launched by the Svenska Geofysiska Föreningen (Swedish Geophysical Society), as an international forum for original and review articles on geophysics. Volume 1, No. 1, dated February 1949, contains 64 pages and carries six articles and two "notes," all in English. Contributions will be accepted in English, French, or German. The annual subscription rate is U. S. $6.00 or Swedish Kr. 21.00. Contributions and subscription orders may be addressed to the Editor, Tellus, Sveriges Meteorologiska och Hydrologiska Institut, Fridhemsgatan 9, Stockholm, Sweden.

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